INL/EXT-11-20792

Objective 1: Extend Life, Improve Performance, and Maintain Safety of the Current Fleet

Implementation Plan

January 2011

U.S. Department of Energy

Office of Nuclear Energy

INL/EXT-11-20792

Objective 1: Extend Life, Improve Performance, and Maintain Safety of the Current Fleet

Implementation Plan

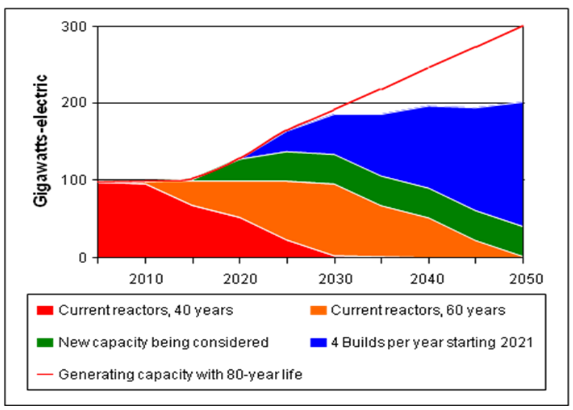
January 2011

Prepared by the
U.S. Department of Energy
Office of Nuclear Energy

EXECUTIVE SUMMARY

Nuclear power has reliably and economically contributed almost 20% of electrical generation in the United States over the past two decades. It remains the single largest contributor (more than 70%) of non-greenhouse-gas-emitting electric power generation in the United States.

By the year 2030, domestic demand for electrical energy is expected to grow to levels of 16 to 36% higher than 2007 levels. At the same time, most currently operating nuclear power plants will begin reaching the end of their 60-year operating licenses. Figure E-1 shows projected nuclear energy contribution to the domestic generating capacity. If current operating nuclear power plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline—even with the expected addition of new nuclear generating capacity. The oldest commercial plants in the United States reached their 40th anniversary in 2009.



The red line represents the total generating capacity of current and planned nuclear power plants, assuming extended operation to 80 years.
The unshaded area below the line represents lost capacity if the current nuclear power plant fleet is decommissioned after 60 years.

Figure E-1. Projected nuclear power generation.

The U.S. Department of Energy (DOE) Office of Nuclear Energy’s Research and Development Roadmap has organized its activities in accordance with four objectives that ensure nuclear energy remains a compelling and viable energy option for the United States. The objectives are as follows: (1) develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of the current reactors; (2) develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration’s energy security and climate change goals; (3) develop sustainable nuclear fuel cycles; and (4) understand and minimize risks of nuclear proliferation and terrorism.

The Light Water Reactor Sustainability (LWRS) Program is the primary programmatic activity that addresses Objective 1. This document describes how Objective 1 and the LWRS Program will be implemented.

The existing U.S. nuclear fleet has a remarkable safety and performance record and today accounts for 70% of the low greenhouse gas emitting domestic electricity production. Extending the operating lifetimes of current plants beyond 60 years and, where possible, making further improvements in their productivity will generate early benefits from research, development, and demonstration investments in nuclear power. DOE's role in Objective 1 is to partner with industry and the Nuclear Regulatory Commission in appropriate ways to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, plant license extensions, and age-related regulatory oversight decisions. The DOE research, development, and demonstration role will focus on aging phenomena and issues that require long-term research and are generic to reactor type. Cost-shared demonstration activities will be conducted when appropriate.

The following five research and development pathways have been identified to address Objective 1:

(1) ***Nuclear Materials Aging and Degradation***. Research to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. Provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operation.

(2) ***Advanced Light Water Reactor Nuclear Fuel Development*****.** Improve scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics.

(3) ***Advanced Instrumentation, Information, and Control Systems Technologies*****.** Address long-term aging and obsolescence of instrumentation and control technologies and develop and test new information and control technologies. Develop advanced condition monitoring technologies for more automated and reliable plant operation.

(4) ***Risk-Informed Safety Margin Characterization*****.** Bring together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management.

(5) ***Economics and Efficiency Improvement.*** Improve economics and efficiency of the current fleet of reactors while maintaining excellent safety performance. Develop methodologies and scientific basis to enable additional extended power uprates. Improve thermal efficiency by developing advanced cooling technologies to minimize water usage. Study the feasibility of expanding the current fleet into nonelectric applications.

The sustainability of light water reactors will benefit enormously from advanced modeling and simulation capabilities. The DOE Energy Innovation Modeling and Simulation Hub, Consortium for Advanced Simulation of LWRs will integrate existing nuclear energy modeling and simulation capabilities with relevant capabilities developed by the DOE Office of Science, the National Nuclear Security Administration, and others to leapfrog current technology to provide a multiphysics, multiscale predictive capability that is a revolutionary improvement over conventional codes. A key challenge will be to adapt advanced computer science tools to an applications environment. The hub is intended to create a new state-of-the-art in an engineering-oriented, multiphysics computational environment that can be used by a wide range of practitioners to conduct ultra-high fidelity predictive calculations of reactor performance.

With the 60-year licenses beginning to expire between the years 2029 and 2049, utilities are likely to initiate planning for baseload replacement power by 2014 or earlier. Research for addressing nuclear power plant aging questions must start now and is likely to extend through 2029. The LWRS Program represents the timely collaborative research needed to retain the existing safe operation of nuclear power plant infrastructure in the United States as long as it can operate safely.

CONTENTS

FIGURES

ACRONYMS

CASL	Consortium for Advanced Simulation of LWRs
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EPRI	Electric Power Research Institute
FY	fiscal year
II&C	instrumentation, information, and control(s)
INL	Idaho National Laboratory
LWR	light water reactor
LWRS	light water reactor sustainability
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk assessment
R7	RELAP7 – Next generation analysis capability
R&D	research and development
RISMC	Risk-Informed Safety Margin Characterization
SSC	systems, structures, and components
TIO	Technical Integration Office

Objective 1: Extend Life, Improve Performance, and Maintain Safety of the Current Fleet

1. IMPLEMENTATION PLAN

1.1 Introduction

The U.S. Department of Energy (DOE) Office of Nuclear Energy's (NE) Research and Development (R&D) Roadmap has organized its activities according to four objectives that ensure nuclear energy remains a compelling and viable energy option for the United States. The objectives are as follows: (1) develop technologies and other solutions that can improve the reliability, sustain safety, and extend the life of the current reactors; (2) develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals; (3) develop sustainable nuclear fuel cycles; and (4) understand and minimize risks of nuclear proliferation and terrorism.

The Light Water Reactor Sustainability (LWRS) Program is the primary programmatic activity that addresses Objective 1. This document describes how Objective 1 and the LWRS Program will be implemented.

Currently, 104 nuclear power plants are operating in 31 states (Figure 1-1). The existing, operating fleet of U.S. nuclear power plants has consistently maintained outstanding levels of nuclear safety, reliability, and operational performance over the last two decades and operates with an average capacity factor above 90%, far superior to the 71% capacity factor achieved just over a decade ago.[a] This significant improvement in performance has made nuclear power plants considerably more economical to operate. Major improvements were made in all areas of plant performance, including operations, training, equipment maintenance and reliability, technological improvements, and improved understanding of component degradation. More broadly, these improvements reflect effective management practices, advances in technology, and the sharing of safety and operational experience. Today, nuclear production costs are the lowest among major U.S. power-generating options.

The oldest operating nuclear power plant started operation in 1969, and the newest plant started operation in 1996. The first group of nuclear power plants was brought online between 1969 and 1979, and the second group between 1980 and 1996. Almost all operating nuclear power plants have been issued, are applying for, or plan to apply for a 20-year license extension. This license extension will result in a licensed operating plant life of 60 years.

In about the year 2030, unless further licensing renewal occurs, the current fleet of nuclear power plants will reach the end of their 60-year operating license period. Absent additional research to address critical plant-aging issues, these valuable generating stations will be retired and decommissioned. Furthermore, degradation and obsolescence threaten to decrease power production from these nuclear power plants even before the scheduled end of their licensed lifetimes. Over the next three decades, this would result in a loss of 100-GWe of emission-free generating capacity and is comparable to electrical generation of new nuclear power plants that may be built over the same time period, leaving a gap in projections of required emission-free generating capacity. This gap might be filled with higher construction rates of new nuclear power plants or with other technologies. However, continued safe and economical operation of current reactors for an even longer period of commercial operation, beyond the

[a] U.S. Energy Information Administration, "Monthly Energy Review June 2010," p. 113.

current license renewal lifetime of 60 years, is a potentially low-risk option to fill the gap and to maintain power generation at a fraction of the cost of building new plants.

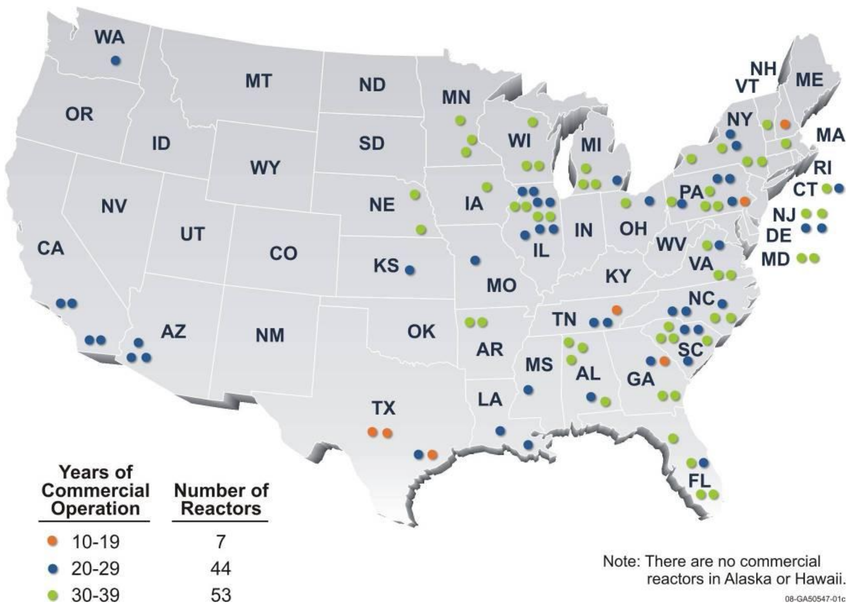


Figure 1-1. National distribution of operating nuclear power plants.

In order to receive a 20-year license extension, a nuclear power plant operator must ensure that the plant will operate safely for the duration of the license extension. The 40-year operating license period established in the Atomic Energy Act was based on antitrust considerations, not technical limitations. The 20-year license extension periods are presently authorized under the governing regulation of 10 CFR Part 54, “Requirements for Renewal of Operating Licenses for Nuclear Power Plants.” This rule places no limit on the number of times a plant can be granted a 20-year license renewal as long as the licensing basis is maintained during the renewal term in the same manner and to the same extent as during the original licensing term.

This regulatory process ensures continued safety of all currently operating nuclear power plants during future renewal periods. The license extension process requires a safety review and an environmental review, with multiple opportunities for public involvement. The applicant must demonstrate safety issues through technical documentation and analysis, which the U.S. Nuclear Regulatory Commission (NRC) confirms before granting a license extension. A solid technical understanding of how systems, structures, and components (SSCs) age is necessary for nuclear power plants to demonstrate continued safety. A well-established knowledge base for the current period of licensed operation exists; however, additional research is needed to establish the robust technical basis that will be required for continued operational evaluations beyond 60 years.

The cost to replace the current fleet would require hundreds of billions of dollars. Replacement of this 100-GWe generating capacity with traditional fossil plants would lead to significant increases in carbon dioxide emissions. Extending operating licenses beyond 60 years would enable existing plants to continue to provide safe, clean, and economic electricity without significant greenhouse gas emissions. The goal of Objective 1 is to provide a comprehensive technical basis for licensing and managing the long-term safe and economical operation of the current fleet of nuclear power plants. The LWRS Program is the primary program that addresses Objective 1.

In developing the strategic plan and more specific program plans, it has become apparent that a government/industry cost-sharing arrangement for R&D is desirable for addressing the long-range, policy-driven goals of government and the acceptability and usefulness of derived solutions to industry. The LWRS Program requires the long-term vision and support of national laboratories and universities to address strategic reliability and safety requirements of existing nuclear power plants that could not be addressed by more inherently tactical organizations. The long-term, higher-risk research required to construct a scientific basis to understand the complex effects of plant aging is not likely to be carried out by industry alone.

The following major challenges face the current fleet:

- Aging and degradation of SSCs, such as reactor core internals, reactor pressure vessel, concrete, buried pipes, and cables

- Fuel reliability and performance issues

- Obsolete analog instrumentation and control technologies

- Design and safety analysis tools based on 1980s vintage knowledge bases and computational capabilities.

The economic incentive to meet these challenges in order to continue safe and reliable operation of existing plants is tremendous. Therefore, the LWRS Program will seek to maximize cost sharing with industry. Industry, working through the Electric Power Research Institute (EPRI) or through various owners' groups, will engage some of these challenges directly; however, those requiring significant research, development, and demonstration without a guaranteed or near-term return on investment will not be explored by industry. Federal R&D investments are appropriate where private investment is insufficient to help make progress on broadly applicable technology issues that can generate public benefits. The government holds a great deal of theoretical, computational, and experimental expertise in nuclear R&D that is not readily available in industry. The benefits of R&D on life extension can be applied to current plants as wells as to advanced reactor technologies still in development.

DOE-NE conducts research, development, and demonstrations that will maximize the national benefit of nuclear energy technology. The role for DOE is to work cooperatively with industry to support and conduct the long-term research needed to inform major component refurbishment and replacement strategies, performance enhancements, plant license extensions, and age-related regulatory oversight decisions. DOE will focus on aging phenomena and issues that require long-term research and develop advanced technology that industry can apply across the existing nuclear power plant fleet.

Secretary of Energy Steven Chu has reiterated the Administration's position that nuclear energy is an important part of the energy mix. He has recognized the importance of nuclear energy in meeting this challenge and supports R&D that can help increase the benefits of nuclear energy. Additionally, the benefits of assisting industry with R&D on life extension apply to current plants. Finally, the government holds a great deal of theoretical, computational, and experimental expertise in nuclear R&D that is not duplicated in industry. DOE-NE intends to proceed in a manner that supports a strong and viable nuclear industry in the United States and preserves the ability of that industry to participate in nuclear projects here and abroad.

DOE-NE research is focused on advancing the science-based understanding of aging nuclear power plants to increase safety and economics in the existing nuclear power plant fleet. This research has a focus on activities that industry and vendors cannot achieve because of the broad scope of the research across the industry or the technical coordination and infrastructure do not allow the work to progress. The relatively small national investment will be supported by very large infrastructure improvements by the industry as the technology for safe and economic operation matures.

Over the past several decades, academia and national laboratories have made enormous advances in the area of general materials science and modeling of fundamental structures. Applications of these sciences, although not specifically nuclear in nature, have the potential to bring tremendous advances over the narrowly focused, step-wise improvements the nuclear industry has realized thus far. Additionally, because of their unique resources (such as experimental irradiation and post-irradiation examination facilities), the national laboratory infrastructure is positioned to bridge the nuclear industry, R&D, and demonstration infrastructures. The LWRS Program serves to facilitate use of this knowledge with further R&D that is specific to the current fleet of nuclear power plants in understanding ongoing and complex challenges to long-term operations.

In summary, the electrical energy sector is challenged to supply increasing amounts of electricity in a dependable and economical manner and with reduced carbon dioxide emissions. Nuclear power is an important part of answering the challenge through long-term safe and economical operation of current nuclear power plants and with building new nuclear power plants. While implementing the Nuclear Energy Roadmap's Objective 1, the LWRS Program is designed to provide, in collaboration with industry programs, the sound technical basis for licensing and managing the long-term safe operation of existing operating nuclear power plants.

2. DESCRIPTION

2.1 Vision

Today's commercial nuclear power plant fleet has reliably produced environmentally friendly power in the United States for decades. As these nuclear power plants reach the end of their original 40-year operating license and enter their first 20-year extended license, sound engineering principles used in designing and building them must be applied to demonstrate their continued safety for a possible second license extension. In order to preserve the option of continued safe and economical operation of these nuclear power plants, a technical basis is required for the utility to evaluate investments in life-extending improvements and for the regulator to accept license extension applications. This implementation plan identifies R&D activities for enhancing scientific understanding of aging mechanisms important to the SSCs in nuclear power plants and to develop methods and technologies for managing plant aging and evaluating safety of nuclear power plants for long-term operation.

The LWRS Program vision is captured in the following statements:

> *Existing operating nuclear power plants will continue to safely provide clean and economic electricity well beyond their first license-extension period, significantly contributing to reduction of United States and global carbon emissions, enhancement of national energy security, and protection of the environment.*
>
> *There is a comprehensive technical basis for licensing and managing the long-term, safe, economical operation of nuclear power plants. Sustaining the existing operating U.S. fleet also will improve its international engagement and leadership on nuclear safety and security issues.*

Extending the life of nuclear power plants is a vital step in meeting the electrical needs of the United States today and in decades to come. By keeping these plants safely in service, the Nation will retain valuable infrastructure and allow additional time to construct new sources of clean, reliable, and secure energy. Until other reliable sources of power are built and placed on the electrical grid, the existing fleet of nuclear power plants is a vital component of the economy.

2.2 Program Goals

The LWRS Program is designed to achieve its vision by addressing long-term operational challenges that face nuclear utilities in the United States. Program goals are to develop scientific understanding, tools, processes, and technical and operational improvements to do the following:

1. Support long-term licensing and operation of the existing operating nuclear power plants to successfully achieve planned lifetime extension up to 60 years and lifetime extension beyond 60 years

2. Support maintenance and enhancement of performance of the existing operating fleet of LWRs to ensure superior safety, high reliability, and economic performance throughout their full lifetime.

2.2.1 Scientific Basis

Nuclear power systems were developed during the latter half of the 20th century. Their development was greatly facilitated by the Nation's ability and willingness to conduct large-scale experiments. Fifty-two test reactors were constructed at what is now the Idaho National Laboratory, another 14 reactors were constructed at the Oak Ridge National Laboratory, and a few others at other national laboratory sites. By today's standards, these large experiments and technology demonstrations were relatively affordable. The nuclear energy community was a rapid adopter of high-end computational modeling and simulation during the 1970s and 1980s. During this period, nuclear power plant designers and regulators developed many of the most demanding simulation models and tools on the most advanced computational platforms available. During the following 20 years, as the pace of nuclear energy deployment in the United States slowed to a halt, continued developments in our understanding of the fundamental science and phenomenology of nuclear power and transformational improvements in computational platforms went largely untapped due to perceived lack of need. This is no longer the case. These tools can now enable a new generation of nuclear power plant designers, fabricators, regulators, and operators to deliver affordable, safe, and environmentally sustainable nuclear power. The current developmental approach embodies the following elements:

- Theory – Based either on first principles or observations made during phenomenological testing, theories are developed to explain fundamental physical phenomena.

- Modeling and Simulation – A range of mathematical models for diverse phenomena at different time and spatial scales are developed and integrated to predict the overall behavior of the system. Key objectives of the modeling and simulation effort are to reduce the number of prototypes and large-scale experiments needed before demonstration and deployment and to quantify uncertainties and design and operational parameters.

- Verification and Validation – Verification and validation are essential parts of the modeling and simulation tools development process to support life-extension decision-making. Verification is done to ensure specifications are complete and mistakes have not been made in implementing the model. It also ensures the model is programmed correctly, algorithms are properly implemented, models do not contain errors, and coding does not contain bugs. Validation ensures the model meets its intended requirements in terms of the methods employed and results obtained. The ultimate goal of validation is to ensure the model addresses the right problem, provides accurate information about the system being modeled, and is accurately used. Validation requires a large amount of data, which are generated and range from small-scale experiments aimed at observation of isolated phenomena or measurements of fundamental properties to targeted integral experiments.

2.3 Implementation Strategy

Three strategies will be implemented in the LWRS Program:

1. Develop the scientific basis to understand, predict, and measure changes in materials and SSCs as they age in environments associated with continued long-term operation of existing LWRs
2. Apply this fundamental knowledge in collaborative public-private and international partnerships, developing and demonstrating methods and technologies that support safe and economical long-term operation of existing LWRs
3. Identify and verify the efficacy of new technology to address obsolescence while enhancing plant performance and safety.

Because of the scale, cost, and time horizons involved in sustaining the current operating fleet of LWRs, achieving the strategic goals of the LWRS Program will require extensive collaboration with industry, NRC, and international R&D institutions. The LWRS Program Technical Integration Office (TIO) was structured to address the technical and management requirements of the program (as discussed in Section 4). The TIO structure also is designed to facilitate interactions with multiple organizations within industry and universities and to maximize the contribution from each partner. In addition, recognizing the need to support education and training of the next generation of scientists and engineers, the following strategic guidelines were established to guide organization and implementation of the program:

- Leverage institutional knowledge and collaborative opportunities between the nuclear industry, national laboratories, universities, and the federal government in developing the basic scientific understanding in predicting key materials and safety margin characterizations
- Using the LWRS Program's vision and goals, build relationships across established relevant research interests, both at international and domestic levels
- Integrate Nuclear Energy University Program projects with selected R&D pathways
- Ensure the LWRS Program is accountable to sponsors, partners, and other stakeholders.

The LWRS Program can be divided into four phases that correspond to the four phases of sustainability (Section 1.2). The following describes the main objectives of each phase and the timeframe applicable to those nuclear power plants with the 60-year license expiring in 2029 and beyond:

- Phase I: Using data and tools, build confidence for the industry to proceed with new applications for extending plant operating licenses beyond 60 years or understand why such extensions are inadvisable (the timeframe for this phase is 2010 to 2015)
- Phase II: Enable the industry to make the decision to invest in plant refurbishments, modernizations, and licenses for extended operation beyond the first license extension (the timeframe for this period is 2015 to 2020)
- Phase III: Apply scientific solutions and continuing technology development to support NRC review and plant capital investment (the timeframe for this period is 2020 to 2030)

- Phase IV: Enable safe and economic operations with the extended operating licenses (the timeframe for this phase is 2030 and beyond).

The implementation schedule (Figure 2-1) is structured to support the following high-level milestones:

- 2010: Ensure long-term, safe operation is an accepted high-priority option for nuclear power generation by industry, DOE, and NRC
- 2015: Build confidence in long-term operation with data and tools
- 2020: Enable industry decision to invest and license for long-term operation
- 2025: Accept advanced tools, methods, and technologies
- 2030: Commence licensed long-term operations.

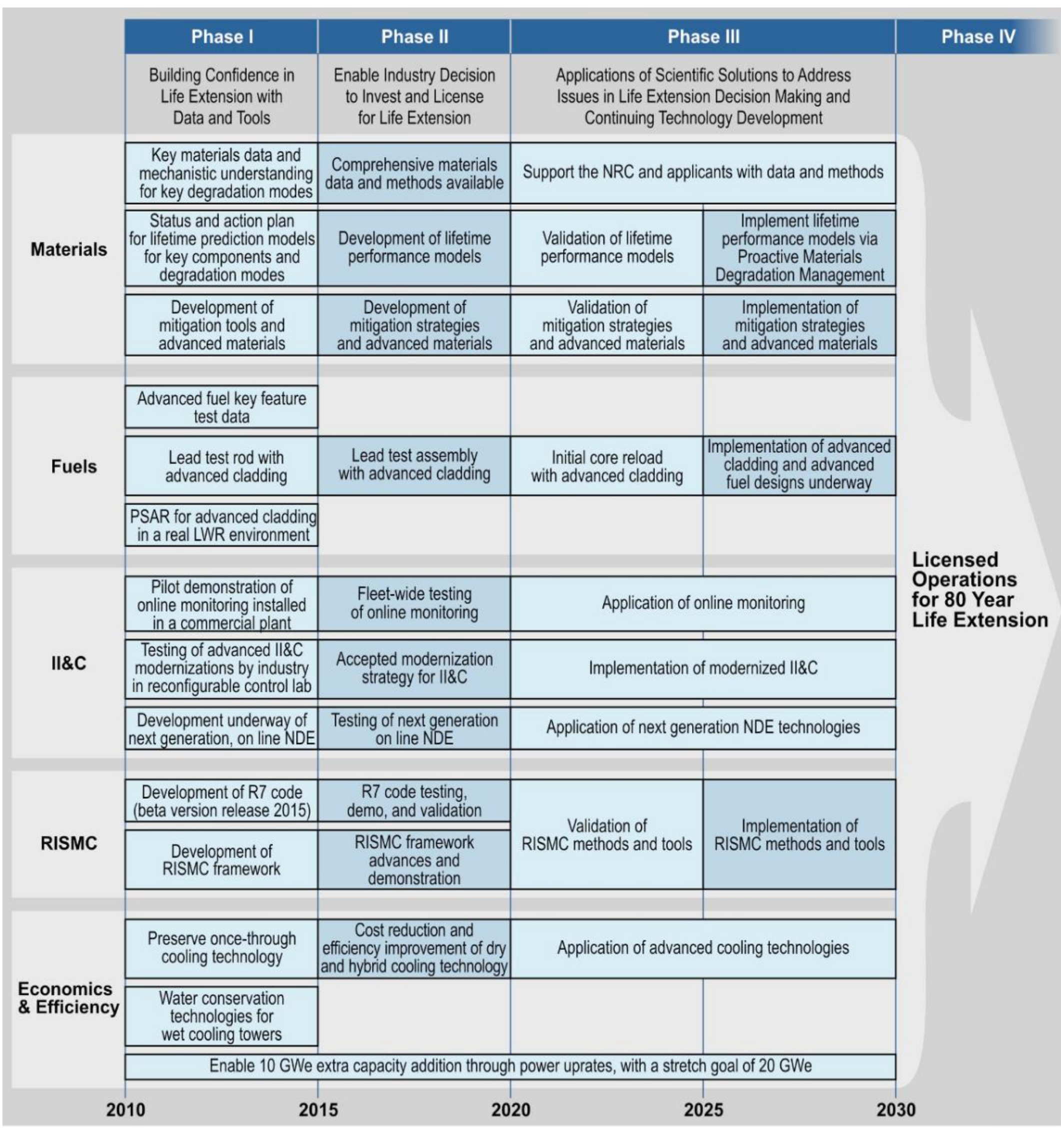


Figure 2-1. Light Water Reactor Sustainability Program implementation schedule.

3. RESEARCH AND DEVELOPMENT PATHWAYS

There are five R&D pathways (i.e., R&D topics) where DOE-NE-supported activities would provide solutions to the challenges encountered and could enable life extension of the reactors beyond 60 years with improved performance. Modest investment in long-term and high-risk/high-reward R&D that supports the current nuclear power plant fleet will provide scientific underpinnings for plant owners to make billion-dollar investment decisions to prolong the economic lifetime of these valuable national strategic assets and improve the lifetime of future generation reactor designs. The following five R&D pathways have been identified to achieve the program vision and address DOE's Objective 1:

1. ***Nuclear Materials Aging and Degradation***. Research to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants. Provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operation.

2. ***Advanced LWR Nuclear Fuel Development*****.** Improve scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants. Apply this information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics.

3. ***Advanced Instrumentation, Information, and Control Systems Technologies*****.** Address long-term aging and obsolescence of instrumentation and control technologies and develop and test new information and control technologies. Develop advanced condition monitoring technologies for more automated and reliable plant operation.

4. ***Risk-Informed Safety Margin Characterization*****.** Bring together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management.

5. ***Economics and Efficiency Improvement.*** Improve economics and efficiency of the current fleet of nuclear power plants while maintaining excellent safety performance. Develop methodologies and scientific basis to enable additional extended power. Improve thermal efficiency by developing advanced cooling technologies to minimize water usage. Study the feasibility of expanding the current fleet into nonelectric applications.

3.1 Nuclear Materials Aging and Degradation

3.1.1 Background and Introduction

Nuclear reactors present a very harsh environment for components service. Components within a reactor core must tolerate high temperature water, stress, vibration, and an intense neutron field. Degradation of materials in this environment can lead to reduced performance, and in some cases, sudden failure.

Materials degradation in a nuclear power plant is extremely complex due to the various materials, environmental conditions, and stress states. Over 25 different metal alloys can be found within the primary and secondary systems; additional materials exist in concrete, the containment vessel, instrumentation and control equipment, cabling, buried piping, and other support facilities. Dominant forms of degradation may vary greatly between different SSCs in the reactor and can have an important role in the safe and efficient operation of a nuclear power plant. A small sampling of these metals for a pressurized water reactor is shown in Figure 3-1.

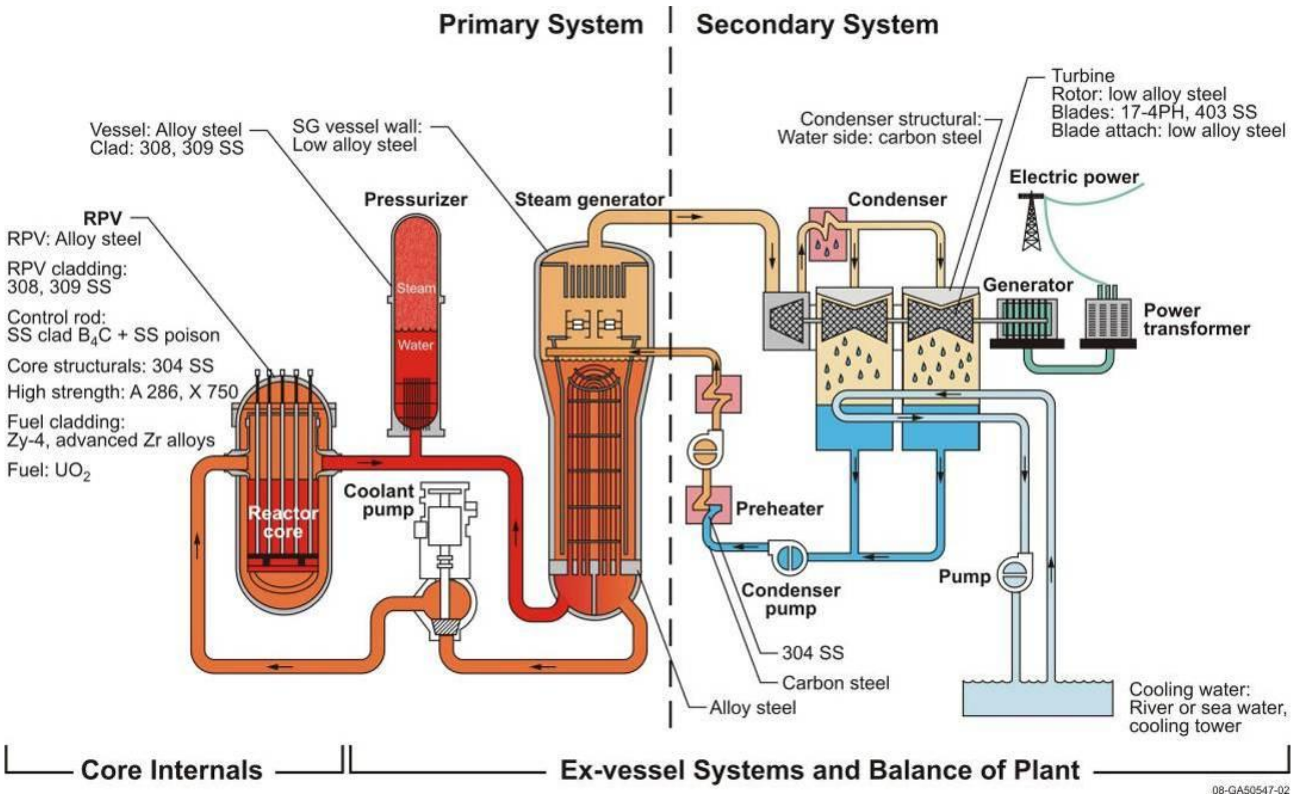


Figure 3-1. Light water reactor metals.

Clearly, materials degradation will impact reactor reliability, availability, and, potentially, safe operation. Routine surveillance and component replacement can mitigate the impact of this degradation; however, failures still occur. With reactor life extensions up to 60 years or beyond and power uprates, many components must tolerate more demanding reactor environments for even longer times. This may increase susceptibility to degradation for different components and may introduce new degradation modes. In many cases, an empirical approach is not practical. In the area of crack-growth mechanisms for Ni-base alloys alone (a single material, degradation mode pair), there are up to 40 variables known to have a measurable effect. Many variables have complex interactions. A purely experimental approach would require greater than a trillion experiments. Application of modern materials science will be required to resolve these issues. In the past two decades, there have been great gains in techniques and methodologies that can be applied to the nuclear materials problems of today. Indeed, modern materials science tools (such as advanced characterization tools and computational tools) must be employed. While specific tools and the science-based approach can be described in detail for each particular degradation mode, many of the diverse topics and needs described earlier can be organized into a few key areas. These could include mechanisms of degradation, mitigation strategies, and modeling and simulation. While all components (except perhaps the reactor pressure vessel) can be replaced, it may not be economically favorable. Therefore, understanding, controlling, and mitigating materials degradation processes and a technical basis for long-range planning for necessary replacements are key priorities for nuclear power plant operation, power uprate considerations, and life extensions.

3.1.2 Vision and Goals

The strategic goals of the Nuclear Materials Aging and Degradation R&D pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations.

Specific outputs from this R&D pathway will include improved mechanistic understanding of key degradation modes and sufficient experimental data to provide and validate operational limits and development of advanced mitigation techniques to provide improved performance, reliability, and economics. Mechanistic and operational data also will be used to develop performance models for key material systems and components in later years.

3.1.3 Highlights of Research and Development

The Nuclear Materials Aging and Degradation R&D pathway activities have been organized into five areas: (1) reactor metals, (2) concrete, (3) cables, (4) buried piping, and (5) mitigation strategies. These research areas cover material degradation in SSCs that were designed for service without replacement throughout the life of the plant. Management of long-term operation of these components can be difficult and expensive. As nuclear power plant licensees seek approval for extended operation, the way in which these materials age beyond 60 years will need to be evaluated and their capabilities reassessed in order to ensure that they maintain the required design functions safely and economically. In addition to the five research areas, a Materials Aging and Degradation Assessment also will be conducted to provide a comprehensive assessment of materials degradation.

3.1.3.1 Reactor Metals. Numerous types of metal alloys can be found throughout the primary and secondary systems. Some of these materials, particularly the reactor internals, are exposed to high temperatures, water, and neutron flux. This creates degradation mechanisms that may be unique or environmentally exacerbated. Research programs in this area will provide a foundation upon which a safe regulatory environment can be established for life beyond 60 years. The following eight activities will encompass the reactor metals area: (1) mechanisms of irradiation-assisted stress corrosion cracking in stainless steels, (2) high-fluence effects on reactor pressure vessel steels, (3) crack initiation in Nickel alloys, (4) high-fluence effects on irradiation-assisted stress corrosion cracking of stainless steels, (5) irradiation-assisted stress corrosion cracking of alloy X-750, (6) evaluation of swelling effects in high-fluence core internals, (7) irradiation-induced phase transformations in high-fluence core internals, and (8) surrogate and attenuation effects on reactor pressure vessel steels.

3.1.3.2 Concrete. Currently, there is little or no data on long-term concrete performance in nuclear power plants. Long-term stability and performance of concrete structures within a nuclear power plant is a concern. The objective of this task is to assess the long-term performance of concrete. Research task evaluation and prioritization will be performed on an ongoing basis. Plans for research will continue to be evaluated by collaborators at EPRI and NRC to ensure complementary and cooperative research. In addition, formation of an Extended Service Materials Working Group will provide a valuable resource for additional and diverse input.

3.1.3.3 Cabling. Cable aging is a concern that currently faces the operators of existing nuclear power plants. Utility companies carry out periodic cable inspections using nondestructive examination techniques to measure degradation and determine when replacement is needed. Degradation of these cables is primarily caused by long-term exposure to high temperatures. Additionally, stretches of cables that have been buried underground are frequently exposed to groundwater.

3.1.3.4 Buried Piping. Maintaining the many miles of buried piping is an area of concern when evaluating the feasibility of continued plant life. While much of the buried pipes comprise either secondary plant or other non-safety-related cooling systems, some buried piping serves a direct safety function. Maintaining the integrity and reliability of all of these systems is necessary for continued plant operation. These systems must be maintained to ensure predictable plant operation and to maintain plant efficiency.

3.1.3.5 Mitigation Technologies. Mitigation technologies include weld repair, post-irradiation annealing, and water chemistry modifications. Welding is widely used for component repair. Weld-repair techniques must be resistant to long-term degradation mechanisms. Extended lifetimes and increased repair frequency welds must be resistant to corrosion, irradiation, and other forms of degradation. The purpose of this research area is to develop new techniques for weldments, weld analysis, and weld repair. A critical assessment of the most advanced methods and their viability for LWR repair weld applications is needed. Post-irradiation annealing may be a means of reducing irradiation-induced hardening in the reactor pressure vessel. It also may be useful for mitigation of radiation-induced degradation of core internals. Water chemistry modification is another mitigation technology that warrants evaluation.

3.1.4 Integrated Research Activities

This research element includes (1) international collaboration to conduct coordinated research with international institutions such as the Materials Aging Institute in order to provide more collaboration and cost sharing, (2) coordinated irradiation experiments to provide a single integrated effort for irradiation experiments, (3) advanced characterization tools to increase materials testing capability, improve quality, and develop new methods for materials testing, and (4) additional research tasks based on results and assessments of current research activities.

3.1.5 Industry Engagement and Cost Sharing

Coordination with other research efforts will be a national program and will require contributions from many different institutions, including input from EPRI's parallel activities in the Long-Term Operations strategic action plan and NRC's Life Beyond 60 activities. In addition to contributions from EPRI and NRC, participation from utilities and reactor vendors will be required. Given the breadth of the research needs and directions, all technical expertise and research facilities must be employed to support long-term operation of the nuclear power plant fleet.

The activities and results of other research efforts in the past and present must be considered on a continuous basis. Collaborations with other research efforts may provide a significant increase in cost sharing of research and may speed up research for both partners. This approach also reduces unnecessary overlap and duplicate work. Many possible avenues for collaboration exist, including the following:

- **EPRI:** Considerable research efforts on a broad spectrum of nuclear reactor materials issues that are currently under way provide a solid foundation of data, experiences, and knowledge

- **NRC:** Broad research efforts of NRC should be considered carefully during task selection and implementation

- **Boiling water reactor and pressurized water reactor owners groups:** These groups provide a forum for understanding key materials degradation issues for each type of reactor

- **Materials Aging Institute:** The Materials Aging Institute is dedicated to understanding and modeling materials degradation; a specific example might be the issue of environmental-assisted cracking

- **Programs in other industries and sectors:** Research in other fields may be applicable in the LWRS Program; for example, efforts in other fields such as the Advanced Cement-Based Materials Program may provide a valuable starting database on concrete performance for structures

- **Other nuclear facilities:** Degradation of concrete, buried piping, and cabling are not unique to nuclear reactors; other nuclear facilities (such as hot cells and reprocessing facilities) may be a key resource for understanding long-term aging of these materials and systems. The primary focus of the Constellation Pilot Project program centers on the material aging effects. This is a significant program commitment.

- **Other nuclear materials programs:** In addition, research within fast reactor and fusion reactor programs may provide key insights into high-fluence effects on materials because the mechanisms and models of degradation for fast reactor applications can be modified and provide a starting and proven framework for degradation issues in this effort.

Participation and collaboration with all of these partners may yield new opportunities for collaboration. Cost sharing also is being pursued for each task. Cost sharing can take many forms, including direct sharing of expenses, shared materials (or rescued specimens), coordinated plans, and complementary testing.

Requested Fiscal Year (FY) 2011 funding for all the planned FY 2011 tasks is $6.0M, and the stakeholder contributions both direct and in-kind support is $6.4M.

3.1.6 Facility Requirements

The core nuclear and radiological facilities needed to support the research of materials aging and degradation issues already exist. Research into irradiation effects and corrosion issues are expected to be the most difficult and considerable resources already exist within the national laboratory, university, and industry network for these issues. For irradiation effects, two test reactors (i.e., the Advanced Test Reactor and High-Flux Isotope Reactor) and the LWR fleet are available. Post-irradiation testing can be performed at the Idaho National Laboratory’s (INL’s) hot cell facilities and the Irradiated Materials Examination Lab, Irradiated Fuels Examination Lab, and Low Activation Materials Development and Analysis facilities at the Oak Ridge National Laboratory, which provide complementary techniques and equipment. Assets for corrosion testing exist at four national laboratories (i.e., Pacific Northwest National Laboratory, Argonne National Laboratory, INL, and Oak Ridge National Laboratory), four universities (the University of Michigan, Massachusetts Institute of Technology, University of Wisconsin, and Penn State), and all reactor vendors. Other Office of Science user facilities (such as Shared Research Equipment Facility at Oak Ridge National Laboratory) and INL’s Electron Microscopy Laboratory provide world-class electron microscopy and characterization tools. Modification and equipment upgrades and modernization will be required on a case-by-case basis.

3.1.7 Products and Implementation Schedule

The main products from the Nuclear Materials Aging and Degradation R&D pathway are (1) mechanistic understanding of key degradation modes, (2) lifetime performance models, (3) advanced mitigation strategies, and (4) advanced replacement materials. The implementation schedule shown in Figure 3-2 is structured to support the following high-level milestones:

- 2010:
  - Complete the first iteration of reactor material degradation matrix
  - Identify the status and potential magnitude of key degradation modes for materials systems and issues.
- 2015:
  - Develop materials data and mechanistic understanding for key degradation modes in hand:
    - Determination of mechanisms of stress corrosion cracking underway
    - Bounding data for reactor pressure vessel embrittlement
    - Concrete degradation
    - Cabling
  - Develop status and action plan for lifetime prediction models for key components and degradation modes
  - Develop mitigation tools and advanced materials options underway:
    - Validation of post-irradiation annealing
    - Development of advanced replacement materials.
- 2020:
  - Ensure materials data and methods are available to support high confidence of successful long-term operation and predictable service times (replacement times) for major components:
    - Validation of lifetime performance models
    - Development of mitigation strategies.
- 2025: Support applicants and NRC with data and methods for materials degradation issues and limitations via proactive materials degradation management.
- 2030: Implement lifetime performance models, mitigation strategies, and advanced replacement materials.

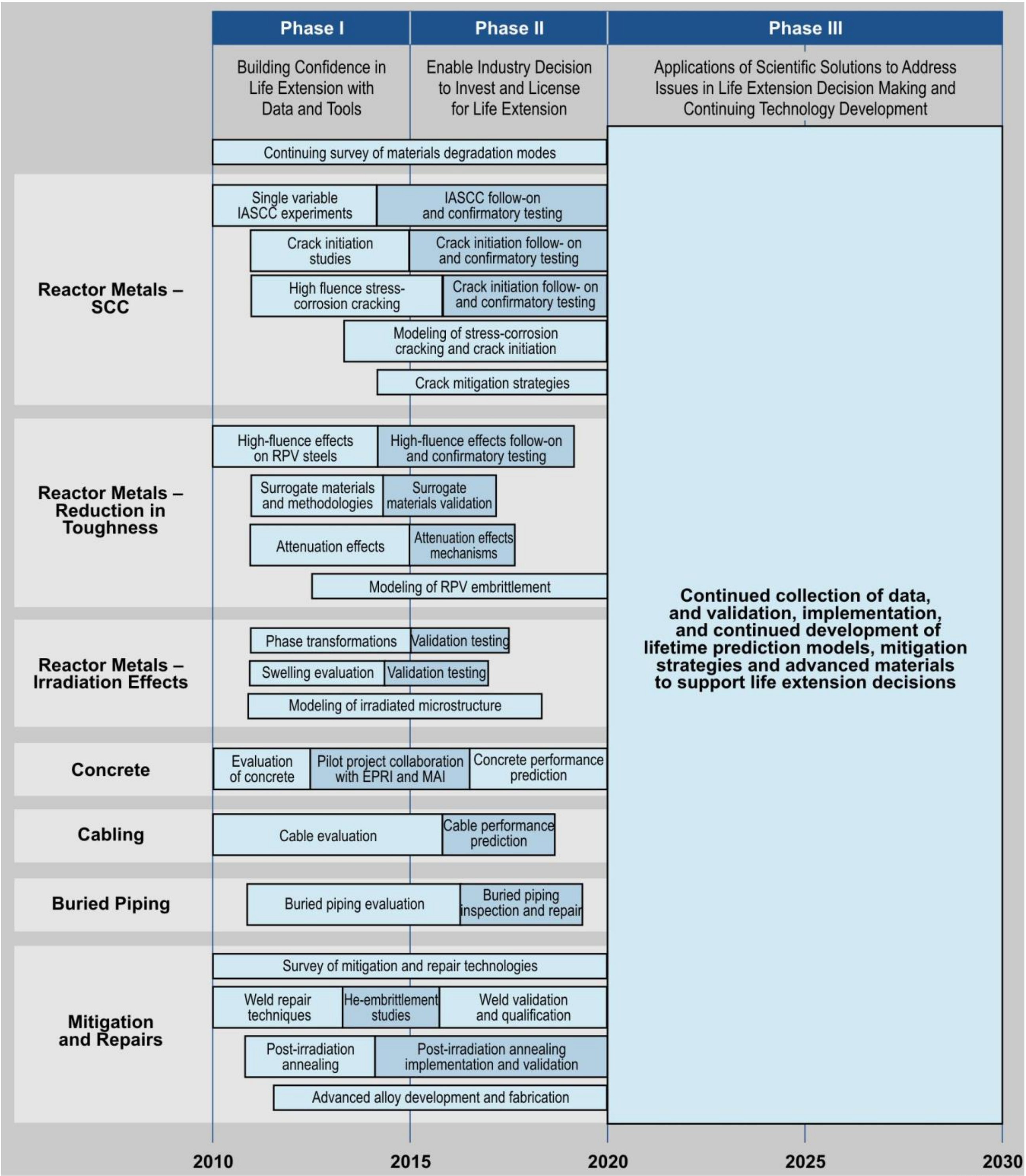


Figure 3-2. Nuclear Materials Aging and Degradation pathway implementation schedule.

3.2 Advanced Light Water Reactor Nuclear Fuel Development

3.2.1 Background and Introduction

Nuclear fuel performance is a significant driver of nuclear power plant operational performance, safety, operating economics, and waste disposal requirements. Over the past two decades, the nuclear power industry has improved plant capacity factors with incremental improvements in fuel reliability and use or burnup. However, these upgrades are reaching their maximum achievable impact within the constraints of existing fuel design, materials, licensing, and enrichment limits. Although the development, testing, and licensing cycle for new fuel designs is typically long (about 10 years from conception through utility acceptance), these improvements are often used with only an empirical understanding of the fundamental phenomena limiting their long-term performance.

Continued development of high-performance nuclear fuels through fundamental research focused on common aging issues can enable nuclear power plant operators to extend plant operating cycles and enhance the safety margins, performance, and productivity of existing nuclear power plants. The Advanced LWR Nuclear Fuel Development R&D pathway performs research on improving reactor core power density, increasing fuel burnups, advanced cladding, and developing enhanced computational models to predict fuel performance. This research is further designed to demonstrate each of these technology advancements while satisfying all safety and regulatory limits through rigorous testing and analysis.

To achieve significant fuel cost and use improvements while remaining within safety boundaries, significant steps beyond incremental improvements in the current generation of nuclear fuel are required. Fundamental improvements are required in the areas of nuclear fuel composition and performance, cladding integrity, and the fuel/cladding interaction to reach the next levels of nuclear fuel development. These technological improvements are likely to take the form of revolutionary cladding materials, enhanced fuel mechanical designs, and alternate isotope fuel compositions. As such, these changes are expected to have substantial beneficial improvements in nuclear power plant economics, operation, and safety.

3.2.2 Vision and Goals

Advanced, high-performance fuels are an essential part of the safe, economic operation of LWRs. New fuels have improved safety margins and economics and are more reliable. Fuel provides head-room for additional power uprates and high burnup limits. The scientific basis for fuel performance is well understood and its response to changing operational conditions and transients is predictable, which supports continuous improvements to reliability and operational flexibility for the nuclear power plant fleet.

Strategic goals are to improve the scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants, and apply this information to development of high-performance, high burnup fuels with improved safety, cladding, integrity, and nuclear fuel cycle economics.

3.2.3 Highlights of Research and Development

The Advanced Nuclear Fuels Development Program element is separated into three R&D tasks: (1) advanced design and concepts, (2) mechanistic understanding of fuel behavior, and (3) advanced tools. These tasks were selected to balance development of new knowledge, verify developed knowledge, and create new advanced fuel technology. The scope of the R&D pathway includes all aspects important to fuel design and performance, including fuel design, exposure effects, and cladding material performance and development. Figure 3-3 shows a typical pressurized water reactor fuel assembly. A boiling water reactor assembly is of different design; however, the fuel rods are quite similar.

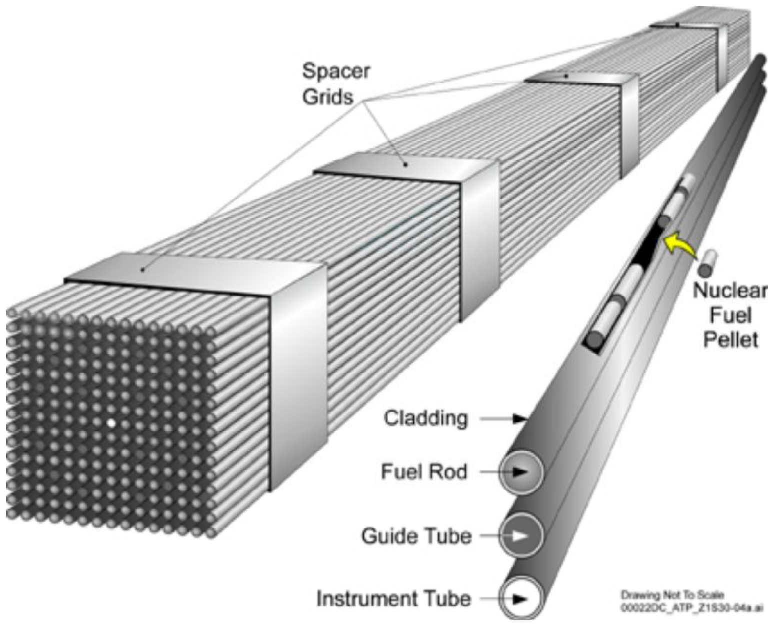


Figure 3-3. Nuclear fuel assembly.

The potential technologies that can be used to achieve the improved nuclear performance include ceramic fuel cladding, nuclear fuel forms, and geometry. Each of these technologies is independently beneficial and can be developed together to maximize the benefit of new materials.

Ceramic fuel cladding may allow for higher strength fuel rods at the high temperatures seen in accident scenarios. Ceramic fuel cladding also has very low chemical reactivity, which will eliminate most corrosion and degradation behavior. Mechanical strength, chemical interactions, effects from radiation, and accident scenarios will need to be studied.

Improved nuclear performance can come from increasing the fissile enrichment content, improved thermal conductivity, and enhanced mechanical strength. The detailed chemistry can be modified to improve thermal conductivity and mechanical strength. Completely new fuel forms may replace the current uranium oxide fuel to achieve significantly different and improved strength and conductivity. These technologies typically require increased enrichment to provide the maximum benefit without compromising current fuel cycle performance. Compatibility with fuel cladding, fuel behavior with increasing use, detailed chemistry effects, behavior during accidents, and the potential requirement for increased enrichment would need to be studied.

Current nuclear fuel pins are cylindrical in shape. Replacing the cylindrical pins with annular or cruciform fuel will increase the surface area to volume ratio. This change can allow higher heat generation rates since more power can be safely removed from the nuclear fuel pin. The higher safe heat rate level will allow increased reactor power without changing the safe operating limits of the reactor. Nuclear fuel behavior, chemistry and corrosion effects, and the accident behavior will need to be studied.

The close coupling of cladding, fuel form, and fuel geometry require sophisticated models and tools to include all performance behavior. Detailed computer simulation is intended to improve predictions of nuclear fuel behavior. This will allow better performance limits, increasing the value of current and future nuclear fuel. A second advantage is to allow an increase in the responsiveness and efficiency of nuclear fuel design.

A significant experimental program is planned to ensure the developed technology is well understood and to develop the intrinsic capability to study new nuclear fuel technology. As the program moves forward and the fuel technology, program infrastructure, and the funding profile mature, additional and supporting technologies also will be developed.

These research areas support each other because development in one area will allow development in the other two areas. This research is designed to demonstrate critical technologies to support nuclear power plant operators in their extended license renewal decision and provide the basis for a new generation of nuclear fuel. The silicon carbide reinforced silicon carbide is a ceramic matrix composite that displays very low chemical reactivity, high hardness, and useful strain before failure and maintains its strength at temperatures that conventional metallic cladding cannot achieve. These material properties offer the opportunity to greatly improve a new generation of nuclear fuel. Maintenance of good structural strength and reduced chemical reaction at elevated temperatures greater than 1,000°C will allow a significant increase in reactor safety. The elimination of exothermic hydrogen reactions seen in zirconium cladding will eliminate a significant nuclear fuel limit, allowing for higher performance and safety. The low chemical reactivity will greatly simplify reactor water chemistry. This will allow optimization of the nuclear power plant water chemistry to protect the vessel internals.

The development of ceramic cladding also demands a much deeper understanding of the fundamental nuclear behavior and material science of the nuclear fuel system. The many design options available to a modern engineered composite allow for many improved performance behaviors. Detailed design of protective glass formation, engineered mechanical properties, and engineered heat transfer properties can be used to optimize fuel cladding performance.

The behavior of ridged ceramic matrix composite cladding and ceramic uranium oxide fuel requires a detailed understanding of nuclear fuel changes at many scales under irradiation. This understanding can be applied to additional or alternate fuel technologies to improve the understanding of safety and performance of nuclear fuel. The insights developed in understanding ceramic matrix composite silicon carbide cladding will be used to address current nuclear fuel issues. The increased understanding will be transferable to other technologies, metallic fuels, annular pellets, cruciform pellets, or higher conductivity fuel, as necessary.

The need for greater understanding of nuclear fuel behavior in a short time also demands a coordinated testing program. The testing program will be used to study new material behavior between ceramic clad and fuel. Testing will define currently unknown behavior to provide information for advanced modeling, pellet clad interaction axial slip, ceramic-ceramic pellet clad interaction, and failure modes of the new fuel. The irradiation program also will provide the basis for a definition of performance properties required to make the licensing case for vendors as the technology matures. The required testing will improve both the physical and knowledge-based infrastructure required for LWR testing. The need for transient testing will require the development of new reactor-based infrastructure. The design, manufacturing, and development of prototype fuel provide a more efficient LWR fuel development process, regardless of the technology focus.

The benefits provided by the current single technology approach include timely results, step change in performance, flexibility in providing industry with technology as development continues, increased fundamental understanding of nuclear technology and improved testing infrastructure.

These activities allow direct product development and development of the supporting enabling technology and understanding required to design and license a new generation of fuel. Without the specific silicon carbide ceramic matrix composite cladding development, another high value fuel development activity would be used to focus fuel development activities toward the roll out of a specific product.

3.2.3.1 Advanced Designs and Concepts. The purpose of this task area is to increase the understanding of advanced fuel design concepts, including use of new cladding materials, increases to fuel lifetime, and expansions to the allowable fuel performance envelope. These improvements will allow fuel performance-related plant operating limits to be optimized in areas such as operating temperatures, power densities, power ramp rates, and coolant chemistry. Accomplishing these goals leads to improved operating safety margins and improved economic benefits.

3.2.3.2 Mechanistic Understanding of Fuel Behavior. This task area will involve testing and modeling of specific aspects of LWR fuel, cladding, and coolant behavior. Examples include pellet cladding interaction, fission gas release, coolant chemistry effects on corrosion, and crud (oxide) formation. Improved understanding of fuel behavior can be used in fuel design, licensing, and performance prediction.

An improved fundamental understanding of phenomena that impose limitations on fuel performance will allow fuel designers, fabricators, plant chemists, and code developers to optimize the performance of current fuels and the designs of advanced fuel concepts. A life-cycle concept will be applied so that optimization applies to fabrication, in-reactor use, and performance as used fuel in storage. Fundamental mechanistic models will provide a foundation for supporting the LWRS Program strategic objectives in developing advanced fuels. The following models will be included in this task: (1) fuel mechanical property change model as a function of exposure, (2) pellet cladding interaction model development, (3) chemistry coolant model development, (4) mesoscale models of microstructure fuel behavior, and (5) hydrogen uptake behavior of zirconium cladding.

3.2.3.3 ***Advanced Tools.*** This task area will use increased understanding of specific fuel performance phenomena that will be integrated into encompassing fuel performance advanced tools. These advanced tools, including modeling and simulation codes, advanced experimental capabilities, and real-time performance monitoring, will be developed to enhance plant and repository efficiency. In addition, the advanced tools developed will be used to minimize the time required to realize the gains made through this R&D effort by decreasing the amount of time needed for materials development and fuel qualification. The following activities will be included in this task: (1) engineering design and safety analysis tool, (2) mechanical models of composite cladding, (3) irradiation design studies of advanced silicon carbide cladding, (4) experimental campaign to verify design and safety margin calculation tool, and (5) advanced mathematical tools to support advanced nuclear fuels calculations.

3.2.4 Industry Engagement and Cost Sharing

An initial activity in FY 2009 was a workshop held with EPRI, nuclear fuel vendors, universities, and DOE laboratories to review potential technologies or combinations of technologies that would best fit the LWRS Program mission. Various specific technologies were proposed, including fuel forms, high thermal conductivity uranium dioxide and a variety of metallic fuels, annular and cruciform fuel geometries, and silicon carbide ceramic cladding materials; other novel ideas were presented and reviewed at the meeting. Silicon carbide fiber reinforced silicon carbide matrix was selected as the initial focus for development. The silicon carbide cladding technology offers the potential for a step change in safety and economics. The implementation schedule for silicon carbide cladding also supports the asset owner’s evaluation before the relicensing decision.

Follow on activities have engaged EPRI as a research partner. The EPRI Advanced Fuels and Fuel Reliability groups have been involved directly in the program. The Advanced Fuels group supports the program as part of the program guidance group with Oak Ridge National Laboratory. They also are supporting the LWRS Program with code support, experimental facilities, and independent fuel behavior research. This interaction has lead to EPRI requesting that the LWRS Program directly support an EPRI research task into the silicon carbide ceramic matrix composite boiling water reactor fuel channels. The goal is to demonstrate the potential for low bow silicon carbide fuel channels. INL will receive a contract for approximately $50K to produce prototypes and test samples. INL will gain fundamental silicon carbide fuel swelling models and knowledge. The LWRS Program also has been invited to attend the EPRI Fuel Users Group meeting.

Westinghouse Electric Company has entered into a nondisclosure agreement with INL/Battelle Energy Alliance that should lead to cooperative R&D agreements on specific research tasks. Currently, INL is receiving commercial zirconium cladding research results. In the future, Westinghouse will supply uranium dioxide fuel pellets and access to testing and irradiation facilities. These commitments will greatly advance the program. The LWRS Program will provide in-kind support with irradiation facilities, materials, and research results.

These interactions are models for industry interaction going forward. The LWRS Program advanced LWR nuclear program element will provide useful infrastructure for testing and advanced technology to leverage with industry partners to advance both programs. The planned near-term results and direct testing programs provide a value to industry.

Industry is working on manufacturing issues of a specific technology related to producing quality functional components that can be used in a commercial reactor. Industry is required to focus on near-term proof of concepts that can lead directly to licensed commercial products. DOE's research is focused on the needed science-based knowledge to confidently understand, design, predict performance, and license advanced fuel. In the case of the LWRS Program with a near-term demonstration of 2015, industry and DOE research activities are very similar as discussed with industry representatives.

3.2.5 Facility Requirements

All fuel development requires the understanding of irradiation effects on fuel performance and relies on irradiation experiments that range from separate effects to integral effects under representative and prototypic conditions. Test facilities for irradiation of advanced nuclear fuels need to be developed to allow the Advanced Test Reactor and the High-Flux Isotope Reactor to irradiate unique size/length samples. This includes the total number of test locations for efficiently simulating LWR neutron environments. The provision of adequate LWR pressure loops to simulate chemistry and temperatures at which advanced fuels will operate is a capability that can be added to the Advanced Test Reactor or procured from other existing reactors such as the Halden Reactor Project. New facilities are required where transient and failure modes can be tested with exposed nuclear fuel to provide an adequate demonstration of nuclear fuel performance for safety analysis. These test facilities exist in Europe at high cost and time requirements. Some transient testing facilities could be installed into the Advanced Test Reactor. The Transient Reactor and Experiment Test Facility reactor (at INL) would provide the required, single-purpose test reactor to provide the range of transients required without interfering with other planned Advanced Test Reactor programs.

Pre and post-irradiation testing facilities that are adequate for producing results in a reasonable time are required. Non-irradiated tests of the prototype fuel to minimize required irradiation testing and to speed initial modeling and design development are primary needs. Some capability exists among DOE laboratories. The bulk of the non-nuclear testing is anticipated to occur at university facilities. Analysis of irradiated samples at microstructure and smaller levels will play an important role in developing detailed fuel performance understanding and models.

The need for people capable of developing sophisticated nuclear fuel models and providing analysis for unique reactor fuel tests is likely to be a limiting factor. This requirement will be filled with DOE, university, and vendor personnel.

3.2.6 Products and Implementation Schedule

Advanced nuclear fuel cladding, nuclear fuel materials, and nuclear fuel geometries are the critical technologies to be developed. The understanding gained and computational tools developed in evaluating and testing the critical technologies will allow for higher performing nuclear fuel and better predictions of nuclear fuel behavior.

The implementation schedule shown in Figure 3-4 is structured to support the following high-level milestones:

- 2010:
  - Design and planning of silicon carbide/silicon carbide fiber rodlet irradiation campaign
  - Rodlet testing planning/design with silicon carbide
  - Rodlet irradiation with silicon carbide
  - Mechanical modeling of silicon carbide/silicon carbide fiber matrix
  - Evaluation of silicon carbide technology for further development
  - Licensing case for silicon carbide applications in commercial applications
  - Out-of-core testing, repeated stress, thermal cycles, and failure modes for advanced fuel.
- 2015:
  - Initial lead test rod design with advanced fuel and planning
  - Rod testing planning/design with advanced fuel
  - Development of advanced fuel with multiple technologies
  - Rod irradiation with advanced fuel.
- 2020:
  - Initial advanced fuel lead test assembly licensing
  - Reload testing planning/design with advanced fuel
  - Reload irradiation with advanced fuel.
- 2025:
  - Initial advanced fuel reload design
  - Initial core reload with advanced fuel

- Irradiation program for increased enrichment bundles
- Irradiation program for increased exposure bundles.

- 2030:
  - Fleetwide implementation of advanced fuel reload under way
  - Lead test assembly for increased enrichment fuel
  - Lead test assembly for increased exposure fuel.
- 2040:
  - Advanced fuel designs
  - Advanced uprated cores using advanced fuel cores.

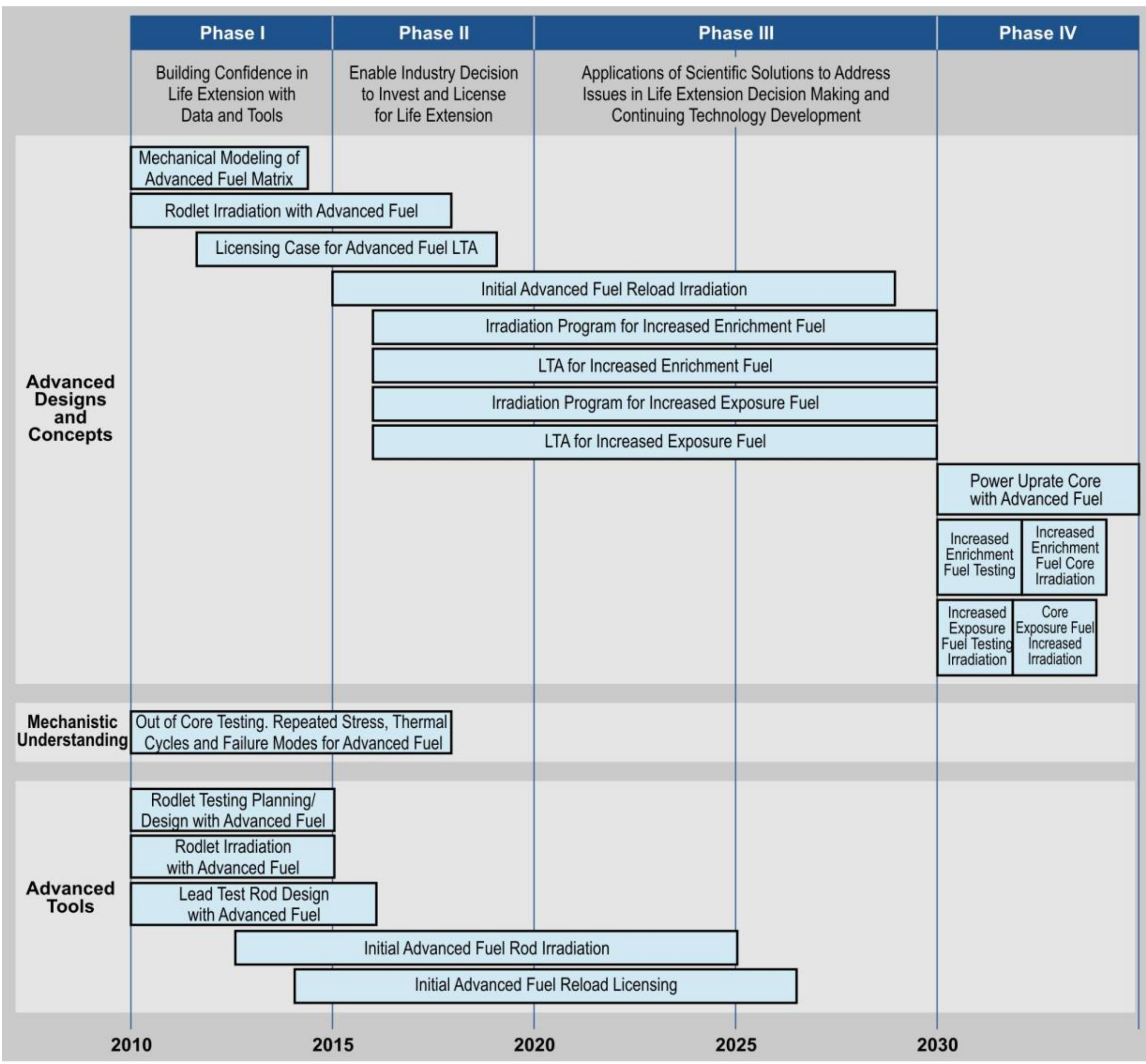


Figure 3-4. Advanced Light Water Reactor Nuclear Fuels Development pathway implementation schedule.

3.2.7 Nuclear Fuels Program Coordination

Advanced nuclear fuel development is not restricted to the LWRS Program. The Advanced LWRS Nuclear Fuels R&D pathway is working in conjunction with other nuclear fuel programs. Direct cooperation with the Fuel Cycle R&D Program (Objective 3) is ongoing. Principal investigators are sharing work packages and attend meetings for both programs. Specific tasks for both programs are being coordinated to avoid overlap but promote progress on required tasks. The LWRS Program has a relatively near-term focus compared to the Fuel Cycle R&D Program. The LWRS Program looks to implement technology in support of the nuclear power plant reinvestment decision. This provides a focus on technologies and supporting tasks that will apply to the current fleet of nuclear power plants.

The Advanced LWRS Nuclear Fuels R&D pathway also is gaining benefit from the Nuclear Energy Advanced Modeling and Simulation Program in development of advanced nuclear fuel computer models. Currently, research for the LWRS Program and the Nuclear Energy Advanced Modeling and Simulation Program use common staff. Close coordination and cooperation among the three fuels-related R&D activities ensures information sharing and avoids potential duplication.

3.3 Advanced Instrumentation, Information, and Control Systems Technologies

3.3.1 Background and Introduction

Instrumentation, information, and control (II&C) systems technologies are essential to ensuring delivery and effective operation of nuclear power systems. They are enabling technologies that affect every aspect of nuclear power plant and secondary plant operations – analogous to a central nervous system. In 1997, the National Research Council conducted a study concerning the challenges involved in modernization of digital instrumentation and control systems in nuclear power plants. Their findings identify the need for new II&C technology integration. Unfortunately, this report, issued in 1997, still reflects the current state of affairs at nuclear power plants. Numerous issues that must be addressed in order to implement new types of II&C systems in commercial nuclear power plants have not been satisfactorily demonstrated in the commercial nuclear power industry of the United States. Without new types of II&C systems, today's nuclear power plants II&C systems will become antiquated and unreliable, unfamiliar to a future workforce, and a liability on the corporate balance sheet.

Figure 3-5. A contemporary control room at a nuclear power plant.

Digital II&C technologies are deployed in a number of power generation settings worldwide. The situation in the United States nuclear power sector differs from these other settings in several key respects: analog systems that have been operated beyond their intended service lifetimes dominate II&C systems in place today; regulatory uncertainty and associated business risk concerns are dominant contributors to the status quo; and current utility business models have not evolved to take full advantage of digital technologies to achieve performance gains. As a consequence, digital technologies are implemented as point solutions to performance and obsolescence concerns with individual II&C components. This reactive approach is characterized by planning horizons that are short and typically only allow for ‘like-for-like’ replacements to be made. This results in a fragmented, non-optimized approach that is driven by immediate needs. As a long-term strategy, this is not sustainable in light of the evolution of II&C technology, availability of skills needed to maintain this antiquated technology, and high costs and uncertainties associated with doing so.

In addition to some of the technical challenges and associated R&D needs, in order to be successful in supporting long-term operational goals, a different approach is needed to encourage digital technology deployment. These must be recognized in light of current industry trends and factors. The first is the rigor of qualification activities needed to deploy new engineered systems in nuclear power plants. Within this power generation sector, II&C specialists frequently refer to the “N” stamp (meaning the nuclear stamp) as shorthand for the rigorous and highly demanding requirements for qualification of II&C technologies intended for integration into nuclear plant II&C architecture. At a minimum, some operational history or tests are needed to demonstrate a commensurate level of safety sufficient to acquire confidence in the new technology. Facilities for research and tests to support these needs are simply lacking in the United States and elsewhere. Also, currently there is little experience in using these kinds of facilities to demonstrate new technologies and produce data that can be used to formulate a regulatory technical basis for digital technology. Rather, most attempts to introduce digital technologies are performed on an as-needed basis by individual utilities. Some of these efforts have resulted in lengthy and very costly efforts and have, according to some, had a chilling effect on other utilities considering a migration to digital technologies.

Second, digital technologies are deployed on an as-needed basis to replace failing analog devices that are no longer maintainable. Because these technologies replace like-for-like capability – analog with digital – the planning horizon for such activities is typically short, which tends to marginalize the potential benefits that can be achieved through digital II&C technology development and deployment Digital replacements of this kind do not displace any of the old costs, but add to them. Hence, digital technologies do not impact the current business models of asset owners or become viewed from the perspective of long-term nuclear asset management. Paradoxically, the potential benefits from additional digital functionality are rarely realized as in other power generation sectors.

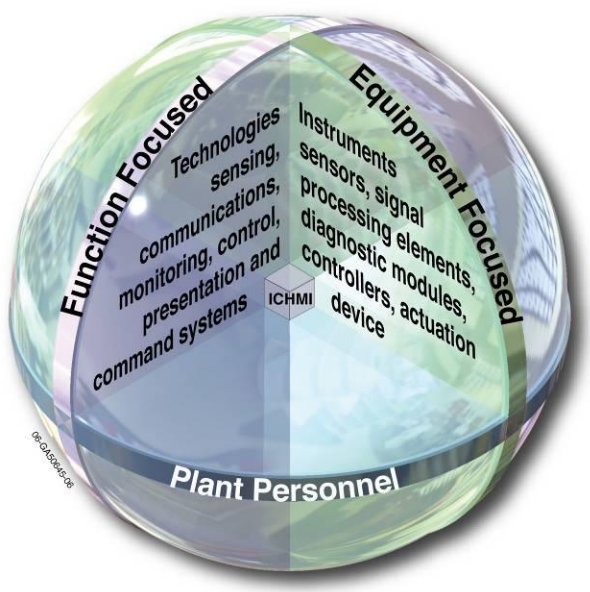
However, the nuclear industry as a whole now recognizes that it is achieving ever-diminishing returns on its constant efforts to improve performance. In part, many of the early potential gains from human performance improvement programs have been achieved and utilities are beginning to recognize that they are approaching the limits of returns on human performance initiatives. Compounding this is the fact that the quotidian costs of energy production in the nuclear power industry continue to be driven by operation and management (i.e., personnel) costs, in contrast to the fossil power generation sector whose daily generation costs are driven by the price of fuel. Individual force-fitting approaches to digital technology deployment and ever increasing obsolescence, long-term safety, and reliability of analog devices necessitate reconsideration of potential solutions involving digital technologies for nuclear energy systems. This reconsideration must include the long-term issues associated with monitoring and managing aging and degradation of plant systems and initiatives that must be undertaken to ensure long-term sustainability of II&C systems in a way that achieves availability of a cost-competitive, reliable nuclear energy supply.

A technology-driven approach in this R&D area alone will be insufficient to yield the type of transformation that is needed to secure a long-term source of nuclear energy base load; a new approach is needed. An effective R&D initiative must engage the perspectives of stakeholders (i.e., asset owners, regulators, vendors, and R&D organizations) in order to articulate and initiate relevant R&D activities.

In order to displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability is needed that leverages the future potential of a range of digital options. This includes consideration of goals for nuclear power plant staff numbers and types of specialized resources; targeting operation and management costs and the plant capacity factor to ensure commercial viability of proposed long-term operations; improved methods for achieving plant safety margins and reductions in unnecessary conservatisms; and leveraging expertise from across the nuclear enterprise. This last point is especially noteworthy because mergers and acquisitions have redefined nuclear asset ownership and nuclear energy supply in the United States and Europe in terms of a substantially reduced ownership set and one that is no longer characterized by regional location or even national boundaries.

3.3.2 Vision and Goals

Maintaining the reliability and safety of II&C systems used for process measurement and control is crucial in meeting the licensing basis of nuclear power generation assets. Aging and obsolescence of the installed technologies is a continuing concern for asset owners. Advances are needed to support crucial characterization and monitoring activities that will become increasingly important as materials age. The aim of collaborations, demonstrations, and approaches envisioned by this R&D pathway are intended to lessen the inertia that sustains the current status quo of today's II&C systems technology and to motivate transformational change and a shift in strategy – informed by business objectives – to a long-term approach to II&C modernization that is more sustainable.



One of the goals of this program is to ensure the issues do not become a limiting factor in the decisions on long-term operation of these assets. Goals for technology introduction are to enhance efficiency, safety, and reliability; improve characterizations of the performance and capabilities of passive and active components during periods of extended operation; and to facilitate introduction of other advanced II&C systems technologies by reducing regulatory uncertainties. The R&D activities of this program are intended to set the agenda for a long-term vision of future operations, including fleetwide integration of new technologies.

3.3.3 Highlights of Research and Development

A program element of R&D activities is proposed to develop some of the specific needed critical capabilities of digital technologies to support long-term nuclear asset operations and management. The supporting technologies will enable the large integrated changes that industry cannot achieve without direct R&D support. This includes comprehensive programs intended to do the following:

- Support creation of new technologies that can be deployed to address the sustainability of today's II&C systems technologies
- Improve understanding of, confidence in, and facilitate transition to these new technologies
- Support development of the technical basis needed to achieve technology deployments

- Develop national capabilities at the university and laboratory level to support R&D
- Create or renew infrastructure needed for long-term research, education, and testing.

3.3.3.1 Centralized Online Monitoring and Information Integration. As nuclear power systems begin to be operated during periods longer than originally anticipated, the need arises for more and better types of monitoring of material and system performance. This includes the need to move from periodic, manual assessments and surveillances of physical systems to online condition monitoring. This represents an important transformational step in the management of physical assets. It enables real-time assessment and monitoring of physical systems and better management of active components based on their actual performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions about asset management and safety management.

3.3.3.2 New Instrumentation and Control and Human System Interface Capabilities. R&D activities are aimed at the eventual modernization of II&C systems technologies used in nuclear energy production. Asset owners and regulators view these as enabling in the dialogue of long-term asset and safety management. The evidence of aged and obsolete technologies is abundant in the control centers of nuclear power plants. The analogy of control rooms as the tip of the iceberg for aging analog technology is particularly apt because it typifies both the problem and a substantial opportunity for R&D to impact systems on a plant scale much larger than what can be readily observed.

Through long-term collaborations with leading international research institutes and capitalizing on new national capabilities for simulation-based technology development and testing, research in visualization, process control, and automation is planned. The long-term objectives of these research activities are to demonstrate new concepts of operations for nuclear power generation assets that address the need for technology modernization, improved state awareness, improved safety, and optimized asset management. These objectives will be achieved by a series of multiyear pilot programs aimed at developing and demonstrating new technologies and concepts for information and control technologies, including the following: (1) advanced instrumentation and information pilot projects, (2) future concept of operations pilot projects, and (3) advanced automation pilot projects.

Advanced instrumentation and information pilot projects will conduct research that employs new instrumentation to monitor and assess the performance of nuclear power plant systems and techniques for using the resulting information (e.g., signals) to improve state awareness, availability, and performance in power generation. Examples of this include instrumentation of major system components (e.g., steam generator and generator) to generate data that can be used with online monitoring technologies, data mining technologies, and other advanced algorithms to provide better real-time information for processing control automation and for plant operators to improve operational efficiencies.

Future concepts of operations will include pilot projects and demonstrations of advanced concepts to enhance information presentation and control technologies for operation, technologies to incorporate centralized expertise for real-time support in operations (e.g., engineering, maintenance, work orders, and support organizations), and promote fleetwide integration of resources. Examples of this include reengineering of control system concepts and demonstrations to leverage the full capabilities of digital technologies for visualization and improved information processing; new assistive technologies to support real-time operational decision making and control; and tools to mine plant data and display results to achieve fine control of plant systems.

Advanced automation pilot projects will conduct research into assistive automation that can provide real-time adaptive control of process systems and reduce the likelihood and consequences of human error and automation failure. Examples of this include development and demonstration of resilient control systems that are mode-sensitive (i.e., sense the plant and system mode and adjust their setpoints and behavior accordingly), can be made more fault tolerant (i.e., individual failures are sensed within the system and are accommodated based on a real-time system model), and are adaptive to system conditions and demands.

3.3.3.3 Nondestructive Examination Technologies. Activities are proposed to develop and test sensors and characterization methods and technologies for a range of nondestructive examination applications. Working closely with the Nuclear Materials Aging and Degradation R&D pathway, this pathway will develop sensors and accompanying technologies to detect and characterize the condition of material parameters needed to assess the performance of SSC materials during long-term operation, including sensors for measuring material properties to derive parameter estimates of specific aging and performance features and analytic capabilities and methods for characterizing the state and condition of material properties in order to obtain 'diagnostic' accuracy about material aging and degradation. This will provide the ability to move from identification of damage and incipient change to more precise descriptions about the underlying mechanisms of change, their progression in materials, and a description of the specific transformations that affect a material or system's ability to achieve its design function.

Activities also are proposed to build on sensors, characterization, and more refined diagnostics to enable prognostic assessments of materials and performance to be made. These capabilities will aid in answering the 'so what' types of questions that arise in connection with material assessments. This entails extending our knowledge and models of materials and material change processes to include predictions about the eventual consequences of change. This requires the need to incorporate information from material science studies and from other R&D pathways and research programs, including international consortia, to develop interim prognostic models that can be validated and improved through bench scale, engineering scale, and accelerated testing to yield models for predicting the effects of different aging mechanisms and associated phenomena.

3.3.4 Industry Engagement and Cost Sharing

A systematic engagement activity is underway with both nuclear asset owners and with NRC. The II&C R&D pathway maintains a dedicated industry-working group, currently composed of eight nuclear utilities and EPRI. The purpose of this working group is to define and sponsor research projects that will collectively enable significant plant performance gains, maintain and improve safety, and minimize operating costs as part of the larger national effort to ensure long-term sustainability of the LWR fleet. Specifically, the working group will do the following:

- Develop agreements with host utilities to demonstrate beneficial digital applications that improve performance at lower cost
- Obtain funding for these projects through a variety of means, such as cost-shared public-private funding and pay-for-performance financial business models
- Coordinate project development among research organizations associated with the U.S. commercial nuclear industry to the degree practical to minimize duplication of effort
- Sponsor research to achieve a long-term vision of the nuclear power plant operating and support model based on substantial digital technology integration, and sponsor research on methodologies to identify the cost-beneficial opportunities to transition various plant support functions to a digital technology infrastructure

- Communicate the work of this research program to utility and support industry decision makers to build a collective vision for a transformed plant operating and support model based on digital technologies

- Coordinate with major nuclear industry support organizations (e.g., the Nuclear Energy Institute, EPRI, and the Institute of Nuclear Power Operations), to the degree practical, in the pursuit of complementary digital technology developments such as appropriate regulatory requirements, technology applications and guidance, and standards of excellence in digital implementation.

Thus far, several workshops have been held with representatives from the industry working group, system vendors, research personnel engaged in this program, and members from NRC. These workshops have been held for the purposes of planning and prioritizing R&D activities in the II&C R&D pathway for both advanced digital II&C technologies and online-monitoring technologies R&D.

The industry working group meets regularly three to four times a year. Certain criteria have been developed for identifying, prioritizing, and selecting potential advanced II&C pilot projects performed by this R&D pathway. These criteria are discussed openly in working group meetings and a consensus approach is fostered.

- A pilot project can be proposed by an individual utility or a group of utilities.

- The pilot project must focus on an aspect of current plant operations and technologies that may contribute to or constitute a roadblock to long-term sustained safe, reliable, or economic performance.

- A pilot project partner utility must have a project designated for work at its own location; it must be funded and appear in a utility master schedule for the year.

- Potential vendors are able to participate in the research so that the results of the effort can be transitioned to a commercially delivered product.

- There is a commitment to attempt to field the system or technologies that are the focus of the pilot project.

- The pilot project partner will make the results of the R&D available and accessible to other commercial nuclear utilities and participate in efforts to support deployment of systems, technologies, and lessons learned by other nuclear asset owners.

Periodic informational meetings are held between DOE Headquarters personnel and members of NRC management to communicate about aims and activities of individual R&D pathways. Briefings and informal meetings will continue to be provided to inform staff from the Office of Regulatory Research about technical scope and objectives of the R&D program. An essential next step is for EPRI and asset owners to identify the best methods of engagement with the regulator through this research program.

Together, these engagement activities are intended to ensure that R&D activities focus on issues of challenge and uncertainty for asset owners and regulators alike, the products of research can be commercialized, and roadblocks to deployment are systematically addressed.

3.3.5 Facility Requirements

A reconfigurable control room and control systems simulation laboratory is planned at INL's Center for Advanced Energy Studies building. This laboratory exists in a scaled version of the facility needed to support R&D of several activities of this R&D pathway. This laboratory will provide the capability to integrate advanced control technologies (e.g., automated procedures, advanced display technologies, and new forms of automation) into a control room and control system environment and will include the capability to conduct human-in-the-loop research. It will have large display and observation areas with quickly reconfigurable physical layouts. The laboratory will coexist with a computer-assisted, virtual environment, high-performance, visualization studio to support rapid prototype, human-in-the-loop, and immersive visualization environments. This laboratory will provide the ability to develop a technical basis for digital technology introduction in an integrated fashion and will address human interaction with emergent instrumentation and control technologies. The main functions and capabilities for this laboratory include (1) process modeling and demonstrations of new technologies, (2) evaluation of digital technology such as system prototyping for new kinds of automation to improve power production efficiencies, (3) usability testing and human-in-the-loop evaluation of operator performance that will be needed as part of future licensing, and (4) advanced visualization and data fusion with process data to support onsite and centralized offsite use and collaborations among experts.

3.3.6 Products and Implementation Schedule

The main products of the Advanced II&C Systems Technologies R&D pathway are as follows:

- Technologies for and demonstrations of highly integrated control and display technologies that address long-term objectives of nuclear power plant operation, including the following:
  - Fleetwide management of asset information to support integrated operations
  - Improved visualization and use of information to support decision-making and actions
  - Greater automation of functions and availability of operator support systems to improve efficiencies and reduce errors
- Online monitoring of active and passive components to reduce demands for unnecessary surveillance, testing, and inspection; minimize forced outages; and provide monitoring of physical performance of critical SSCs
- Nondestructive examination technologies for characterizing performance of physical systems in order to monitor and manage the effects of aging on SSCs.

The program activities occur in three phases (see Figure 3-6). Phase I (FY 2010 to FY 2015) R&D activities are intended to create technologies with new functional capabilities. The objectives of this phase are to create and demonstrate new capabilities to achieve the objectives and vision of long-term asset operation. Phase II (FY 2015 to FY 2020) R&D activities will create more mature technologies that are capable of some field deployments, pilot projects with asset owners, and consortia. During Phase III (FY 2020 to FY 2030), the technology maturity and success with initial deployments will lead to and motivate a shift in the technology base for II&C systems used during long-term operation. Fleetwide deployments and standardization of technology will be ongoing and more R&D activities will lead to greater regulatory engagement and acceptance.

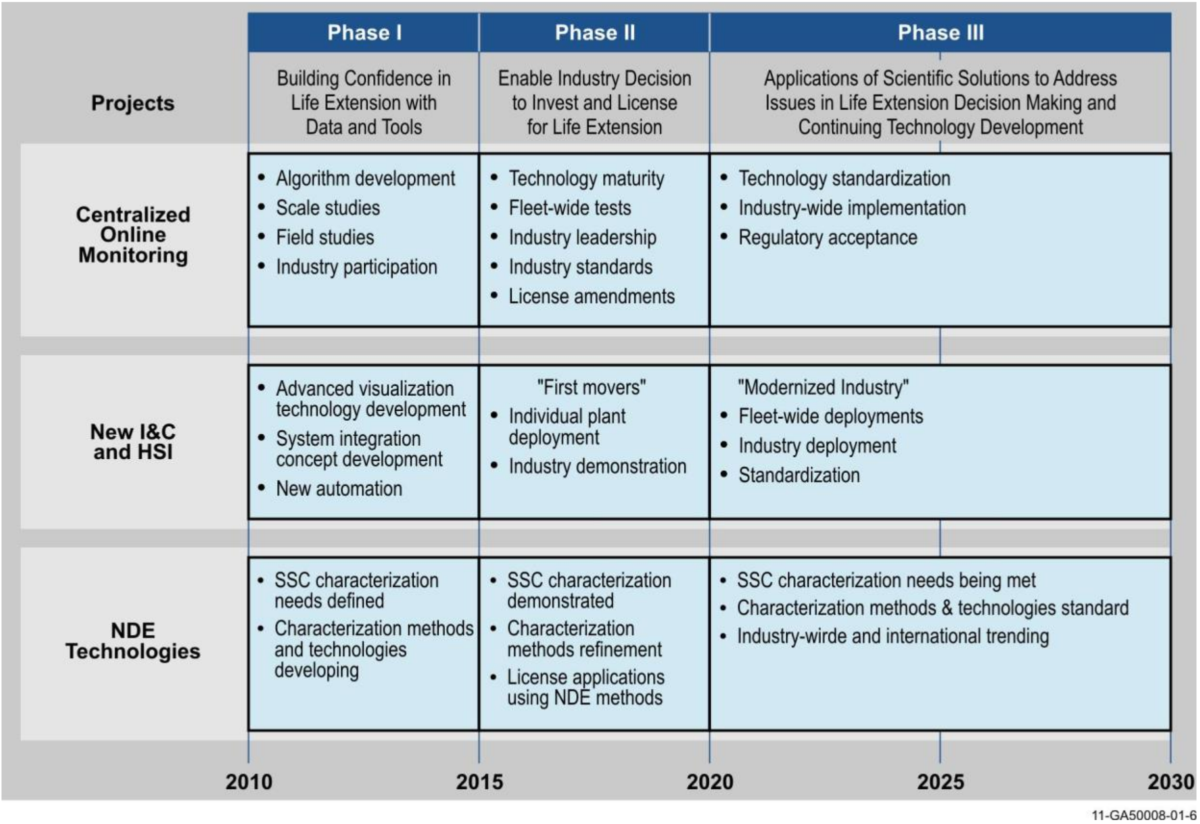


Figure 3-6. Advanced Instrumentation, Information, and Control Systems Technologies pathway implementation schedule.

3.4 Risk-Informed Safety Margin Characterization

3.4.1 Background and Introduction

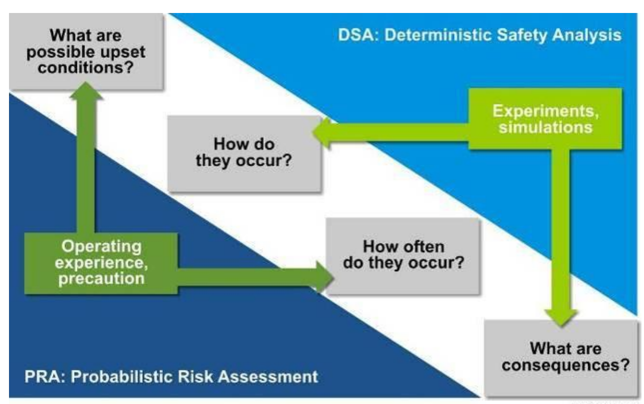


Figure 3-7. Nuclear plant safety analysis.

The Risk-Informed Safety Margin Characterization (RISMC) R&D pathway focuses on advancing the state-of-the-art in safety analysis and risk assessment to support decision making on nuclear power plant life extension beyond 60 years. A comprehensive approach involves four questions that need to be addressed and resolved from the risk and safety perspectives (Figure 3-7). With the plant life extension well beyond the originally licensed operating period, the safety questions take on additional significance due to plant aging (namely how plant aging affects the answer to the four questions). In particular, aging of SSCs has potential to increase frequency of initiating events of certain safety transients; create new sequences associated with previously-not-considered SSC failures; and increase severity of safety transients due to cascading failures of SSCs.

In parallel with a deterministic safety analysis approach, probabilistic risk analysis (PRA) methods have been developed and applied to analyze the safety of nuclear power plants. Notably, safety margins calculated by the deterministic safety analysis methods (e.g., accident simulation codes and structural capacity codes) are used to support the specification of "success criteria" in the plant's PRA. Pioneered by the "Reactor Safety Study" (WASH-1400 1975), the PRA technology has matured and currently provides the nuclear power industry and the regulator with powerful tools to analyze plant safety, identify system vulnerabilities, provide a framework for effective resource allocation, and focus research and plant operations on risk-significant safety threats.

3.4.2 Vision and Goals

Safety is central to design, licensing, operation, and economy of nuclear power plants. As the current LWR nuclear power plants age beyond 60 years, there are possibilities for increasing the frequency of equipment failures that initiate safety-significant events and for creating new failure modes. Accurate characterization of plant safety margins can play an important role in facilitating decision-making related to LWRs. In addition, as R&D in the LWRS Program and other collaborative efforts obtain new data and improve scientific understanding of physical processes that govern materials aging and degradation and develop technological advances in nuclear reactor fuels and plant II&C, there are needs and opportunities to manage plant safety, performance, and assets in an optimal way.

For several reasons, this R&D pathway is built around the idea of analyzing margin. First, as noted above, margin has long played a significant role in consideration of safety. Second, in order to support practical decision-making in so complex an arena, it is imperative to provide the decision-maker with a compact presentation of the safety case, the present vision being to do that in terms of key safety margins. This will be discussed further in Section 3.4.3.1. Finally, explicit analysis of margin drives the evaluation down to the engineering physics in a way that is more useful than just quantifying probabilities as done in a typical PRA.

The strategic objectives of the RISMC R&D pathway are to bring together risk-informed, performance-based methodologies with scientific understanding of critical phenomenological conditions and deterministic predictions of nuclear power plant performance, leading to an integrated characterization of public safety margins in an optimization of nuclear safety, plant performance, and long-term asset management. The RISMC R&D pathway aims to develop an integrated framework and advanced tools for safety assessment that enable more accurate characterization and visualization of the plant's safety margins.

These objectives are currently focused on plant decision-making, which includes NRC-related decision-making as a special case. NRC requirements protect the public, but do not necessarily protect the plant investment. In principle, therefore, the scope of the "risk-informed" margin evaluation includes a broader class of issues and SSCs than has been included in design-basis accident analysis or potentially even in PRA space. For example, events that do not pose a significant threat to public safety may pose a significant threat to plant economics by forcing a prolonged shutdown or perhaps a major component replacement. PRA does not typically analyze for those outcomes.

3.4.3 Highlights of Research and Development

The RISMC R&D pathway is driven by recognition that risk-informed plant safety margins present an avenue for enhancing operational flexibility and safety benefits obtained from the transition toward risk-informed and performance-based regulation. Tools used today in deterministic and probabilistic safety analysis are not adequate to cost-effectively manage the risk and operability significance of aging of SSCs. Therefore, there are conceptual and technical "capability gaps" (in frameworks, tools, and data) that need to be filled to enable integrated and defensible decision-making regarding the continued operation of nuclear power plants after their current license terms.

Once matured and established, RISMC developments will benefit the LWRS Program objectives by (1) creating a strong technical basis for an enhanced risk-informed regulatory structure that enables optimization of plant operation, inspection, maintenance, and replacement of plant SSCs, (2) enabling effective long-term management of plant resources (for which accurate characterization and prediction of safety margins are prerequisite), and (3) helping guide R&D planning toward maximum payoff from both resource utilization and risk perspectives.

RISMC technical work is organized into three major areas (illustrated in Figure 3-8 and discussed in following subsections).

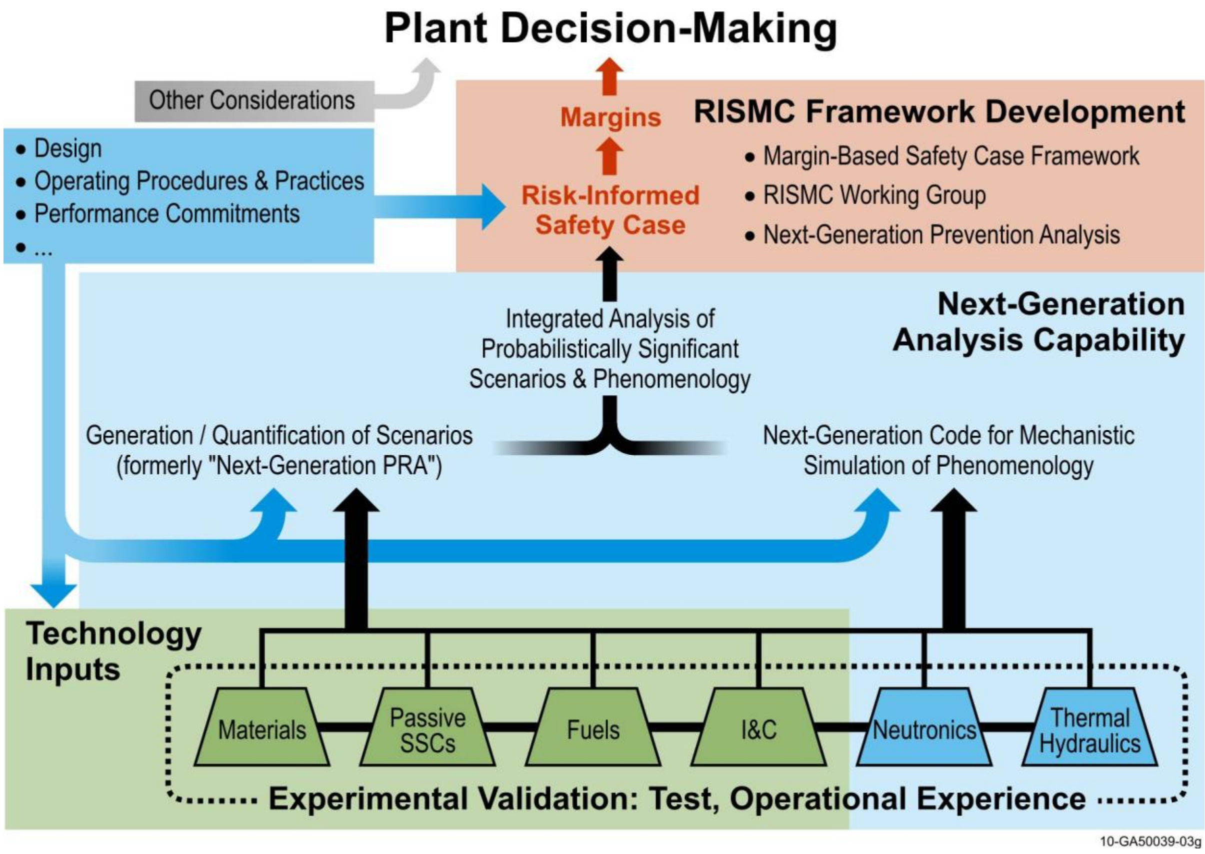


Figure 3-8. Work in Risk-Informed Safety Margin Characterization.

3.4.3.1 Risk-Informed Safety Margin Characterization Framework Development. The purpose of the framework portion of RISMC is to develop a risk-informed life extension safety case and summarize this case to the plant decision-maker in terms of a set of key margins. While definitions may vary in detail, "safety case" means essentially the following:

> *A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is adequately safe for a given application in a given environment.*

For RISMC purposes, life extension safety case means the following:

> *The body of evidence and reasoning that either convincingly justifies a decision to proceed with life extension, or caveats such a decision, by showing where important SSC margins are either insufficient or trending towards insufficiency.*

Neither of the above definitions is explicitly restricted to a particular type of safety or performance requirement. In nuclear facility licensing, the safety case addresses NRC requirements. For a plant decision-maker, the decision would be based on consideration of risk metrics, including metrics addressing risk to plant availability or major capital items. As argued elsewhere, the needs of the plant decision-maker are more demanding than those of NRC in many respects. NRC may deem plant operation allowable; the plant decision-maker needs to make sure that it is economically viable.

Two types of issues are currently deemed significant within RISMC:

1. Issues associated with the capabilities of major components (such as the reactor vessel) under long-term operating conditions

2. Issues associated with possible changes in plant configuration or operation to improve economics.

Both of these types of issues can be analyzed in terms of margin.

Optimal development of a safety case calls for selection of a set of SSCs and associated levels of performance margin as the backbone of that safety case. Prevention analysis is the name that has been given to one specific way of doing this. Prevention analysis works by driving a risk model backward. Most applications of risk models proceed by estimating SSC performance margin (or in practice, directly estimating failure probability) *a priori*, and using that information to synthesize plant risk estimates for comparison with objectives. This supports a trial-and-error approach to optimization of the level of performance credit taken for each item. In contrast to that approach, prevention analysis starts with a desired top-level safety objective and determines what level of SSC performance margin (or in most extant applications, what failure probability allocation) would need to be credited in the risk model in order to optimally satisfy that safety objective (in this case, optimality means crediting a complement of equipment and associated performance margins that is *necessary* and sufficient to do the job). The solution to this is not unique; correspondingly, prevention analysis presents the decision-maker with alternative strategies for satisfying top-level objectives. These strategies can be ranked with respect to difficulty and expense of implementation. In short, prevention analysis identifies a complement of nuclear power plant capabilities that, taken together, serve to prevent accidents to the degree specified by the top-level safety objective.

It is clear that any coherent approach to safety case development is essentially equivalent to a prevention analysis thought process, and some applications of prevention analysis have been based on margin considerations. Therefore, it is technically straightforward in principle to use prevention analysis within RISMC. However, adapting prevention analysis tools to develop the life extension safety case will break some new ground conceptually, and there is no extant application that couples prevention analysis tools to phenomenology simulations. How best to apply prevention analysis within RISMC will be explored beginning early in FY 2011.

3.4.3.2 Next-Generation Analysis Capability (Enabling Methods and Tools).

Characterization of nuclear power plant safety margins is difficult because of large uncertainties that exist in modeling and predicting behaviors of aging SSCs in a broad range of nuclear power plant operating and abnormal conditions and nuclear power plant system dynamics in accident scenarios involving SSC failure modes not studied before. Moreover, existing analysis methods are ill-suited to analyze reliability of the plant's passive SSCs and plant phenomenology in a coupled way, making them suboptimal for analyzing change in margin due to aging. The RISMC R&D pathway is addressing these issues through development of a next-generation analysis capability, which is referred to within the project as RELAP7 or in its shortened form R7.

3.4.3.2.1 Mechanistic Simulation of Phenomenology (Right-Center Portion of Figure 3-8)—Although incremental advances were made continuously over the past two decades to improve modeling of plant components and transient/accident phenomena, the system (plant) analysis tools used in industry's engineering applications remain based on decades-old modeling framework and computational methodology, which have not taken advantage of modern developments in computer/computational science and engineering. Fundamental limitations in the current generation of system analysis codes are well known to the community of safety analysis professionals. Although the codes have served as an adequate basis to address traditional safety margin analysis, significant enhancements will be necessary to support the challenges of extended and enhanced plant operations. This was the initial impetus for embarking on R7. It now emerges that the new methods being applied in R7 lend themselves naturally to addressing the broader issues raised within a risk-informed, decision-making paradigm, as discussed in the following subsections.

3.4.3.2.2 Generation/Quantification of Scenarios (Left-Center Portion of Figure 3-8)—Although state-of-practice PRA makes some high-level use of certain thermal hydraulic analyses, the usual coupling between thermal hydraulic and scenario-based risk modeling is nowhere near to being close enough to support evaluation of RISMC. Efforts to transcend the 1970s PRA paradigm have been made periodically; these efforts incorporate dynamical considerations that are all but suppressed in existing PRAs and try to couple directly to mechanistic codes like RELAP. Within RISMC, R7 is being implemented in a way that straightforwardly allows for simulation of PRA component failure modes within time histories as part of the assessment of margin. This complements ongoing work by EPRI under its Long-Term Operation program, developing a next-generation tool to improve on current standard PRA capability.

3.4.3.3 Technology Inputs. Figure 3-8 (green area in lower left portion) shows technology areas to be integrated into R7. Materials, fuels, and instrumentation and control represent new developments in the corresponding LWRS R&D pathways. Currently, RISMC is not actively integrating new developments from those pathways, but will be in the future.

The "Passive SSCs" area is not a pathway in itself, but is called out for special emphasis in the figure to promote focus on the issue of aging of passive components. Apart from specialized application areas (such as seismic PRA), most current PRA methodology takes most passive SSCs for granted because it is believed that failure of these components does not contribute significantly to offsite risk. Within the LWRS Program, it is important to challenge that presumption and to examine whether margin issues could emerge for SSCs whose performance is presently taken for granted.

As a result of work done in the last year, the current plan is to develop models of passive SSC behavior that are part of R7 and couple directly to plant physics parameters (e.g., temperature cycling, pressure cycling, and neutronics) simulated within R7.

3.4.4 Industry Engagement and Cost Sharing

Industry is very significantly engaged in RISMC activities, and the level of the engagement is increasing. Up to now, industry engagement in RISMC (primarily through EPRI) has taken place at two levels: (1) input into program planning, and (2) active participation in RISMC Working Group activities.

One effect of this influence has been strengthening of the RISMC team consensus that RISMC developments should be driven by "use cases" (i.e., explicitly planned eventual applications that are used to formulate requirements on development of the next-generation capability) and "case studies" (i.e., actual applications that scope particular developments and once completed, support assessment of the current phase of development). Use cases have already played a significant role in the formulation of requirements on the next-generation analysis capability. Beginning in the latter part of FY 2010, EPRI and other industry representatives (the Nuclear Energy Institute representatives and independent consultants) are becoming increasingly involved in detailed technical planning of the case studies that now drive development activities and are expected to support actual execution. This has two effects: (1) it helps to ensure that the program moves in a direction that addresses practical industry concerns, and (2) it provides the RISMC team with access to engineering expertise that is needed in the development of enabling methods and tools discussed in Section 3.4.3.2, especially the formulation of component models and in the case studies performed with those tools.

Coordination of RISMC activities includes the following:

- **EPRI:** As stated above, EPRI will continue to play an important role in high-level technical steering and in detailed planning of RISMC case studies. RISMC work is coordinated with EPRI Long-Term Operation Program work.

- **Other Industry Partners:** Involvement of engineering and analysis support from industry is presently foreseen in the performance of case studies to drive next-generation analysis development and in the formulation of component models for implementation in next-generation analysis capability. The level of analysis effort to be provided and the source of financing for that effort are being negotiated. The individuals prospectively involved are either industry consulting firms or currently-independent consultants who have working relationships with current licensees. All are experts in applying traditional safety analysis tools and are conversant with risk-informed analysis.

3.4.5 Facility Requirements

In science-based, risk-informed safety analysis, new types of data are needed to enable quantification of uncertainty in advanced methods and tools, particularly in multiscale and multiphysics simulation. Infrastructure is needed to support a network of separate-effect tests on nuclear thermal-hydraulics (e.g., facility to measure critical heat flux) and LWR integral test facilities. Large-scale integral test facilities provide the most credible data needed by regulators for safety code qualification. Many integral facilities that represent the existing Gen II plant designs were decommissioned. The facilities that do remain are focused on the passive designs of Gen III+ plants. Even when they existed, facilities like Semiscale and Loss of Fluid Test Facility had a narrow focus on loss-of-coolant accidents for supporting design-basis emergency core cooling system analysis. Within a risk-informed approach, there is a need to validate system safety analysis codes in a much broader space of scenarios and conditions. In particular, sequences identified as risk significant may include those with tight coupling between processes in the reactor cooling system and in the containment system, with multiphysics (e.g., neutronics, thermal hydraulics, coolant chemistry, and structural mechanics) and eventually human factors. This scope presents the need for new data to support R7 code development and validation. This need can be met by modernizing and extending the experimental infrastructure for reactor safety research, which already includes a network of integral test facilities (e.g., APEX and PUMA) and separate effect test facilities located in universities and other institutions across the country and internationally.

3.4.6 Products and Implementation Schedule

The main products of the RISMC R&D pathway are as follows:

- Next-Generation Safety Analysis Code (R7) – A system code that does the following:
  - Performs mechanistic description and effective simulation of plant transient behavior under a broad range of upset conditions and sequences of risk importance under life extension operation
  - Incorporates models of reactor component performance and reliability into the simulations and properly models coupling between the scenario physics (e.g., thermal hydraulics and neutronics) and these aspects of component behavior
- RISMC framework – A comprehensive methodology that applies R7 to support life extension decision-making by bringing together advanced modeling, simulation and analysis tools, and relevant data to characterize nuclear power plant safety margins, including the effect of plant aging
- Enabling methods and tools for advanced PRA and advanced prevention analysis to support life extension decision making.

The implementation schedule (Figure 3-9) is structured to support the following high-level milestones:

- 2010
  - Formulation of RISMC methodology
  - Development, selection, implementation, and testing of architectural features and solution techniques for a next-generation safety analysis code.
- 2011
  - Within the technical scope defined by first-round case studies, development of the next-generation safety analysis code (R7) to simulate plant dynamics and compute safety margin
  - Development of a risk-informed, simulation-driven methodology to apply the R7 in safety system analysis and uncertainty quantification
  - Development of models of passive SSCs for application within the next-generation safety analysis code, in order to directly simulate the coupling between plant physics and SSC reliability and performance.
- 2012
  - Completion of the development of the next generation safety analysis code, the associated framework, and associated models of component behavior to the technical scope of the first-round case studies

- Extend the capability from small-scale demonstration of algorithmic features to plant-scale evaluations of issues of current interest, focusing on the first-round case studies being coordinated with industry

- With industry, define more broadly scoped case studies to drive the next stage (second round) of RISMC development.

- 2015

  - Based to the extent practical on available test and operating data, complete second-round RISMC development (e.g., phenomena modeling, component behavior modeling, and operator performance modeling)

  - Complete second-round case studies, including application of next-generation safety analysis code, next-generation prevention analysis, and integration of component behavior/T/H behavior into the assessment

  - Train a broader set of outside users in application of the RISMC framework and next-generation safety analysis code

  - As of 2015, R7 should support plant decision-making for most safety issues.

- 2020

  - Ensure development and validation to the degree that the RISMC framework and tools are the generally accepted approach for risk-informed, plant decision-making and risk-informed, regulatory decision-making

Figure 3-9 shows the intended schedule of development, whose details necessarily depend on the actual funding profile. Note that the color coding in Figure 3-9 is keyed to Figure 3-8.

Development is planned to take place in phases, rather than trying to deliver a “complete” but completely untested package at the end of the process. It has been agreed with industry to focus in Phase I on modeling a particular pressurized water reactor functional sequence in order to specify a scope of phenomena, components, and code capabilities needed to address that sequence, yielding a product at the end of the first round of development that will have only a partial scope of applicability, but will be testable and verifiable within that scope. Depending on the funding profile, it is currently expected that this first round of development will be complete at the end of 2012. As the first round nears completion, a more challenging set of case studies will be chosen to drive the second round, and a process analogous to that of the first-round development will occur.

It is expected that development of the framework will be substantially complete in the first round, including illustrations of margin characterization and methods for driving R7 to assess margin within the scope of first-round case studies. Refinement of the framework would continue thereafter at a level of effort significantly reduced compared to the effort associated with R7 development.

In the first round, R7-compatible models of passive SSC components also will be developed. As other pathways develop models and results to be input to margins assessments, these will be addressed beginning in the first round and continuing more intensively in the second round. Application of test and operating data to R7 calibration and model testing will begin in the first round with data used to validate existing safety analysis codes. As newer data become available to address issues not covered by those old data, comparison with those data will support R7 refinement. However, note that collection of those data per se is not a RISMC milestone.

The lower portion of Figure 3-9 shows that, beginning in the second round of Phase I development, inputs from other R&D pathways will become available and will be incorporated into R7. This does not mean that R7 is currently proceeding without consideration of fuels issues, materials issues, or II&C issues, but only means that new results from those pathways will begin to inform R7 development on that timeframe.

Assuming a funding profile commensurate with that in the current program plan, R7 development is expected to be substantially complete in 2015 at the end of the second round. This does not mean that R7 would be frozen as of 2015, any more than previous-generation safety analysis codes have been frozen, but its development would be more evolutionary in nature.

Beginning in 2012 and continuing thereafter, increasing effort will be devoted to training a broader user community of practice and supporting their applications.

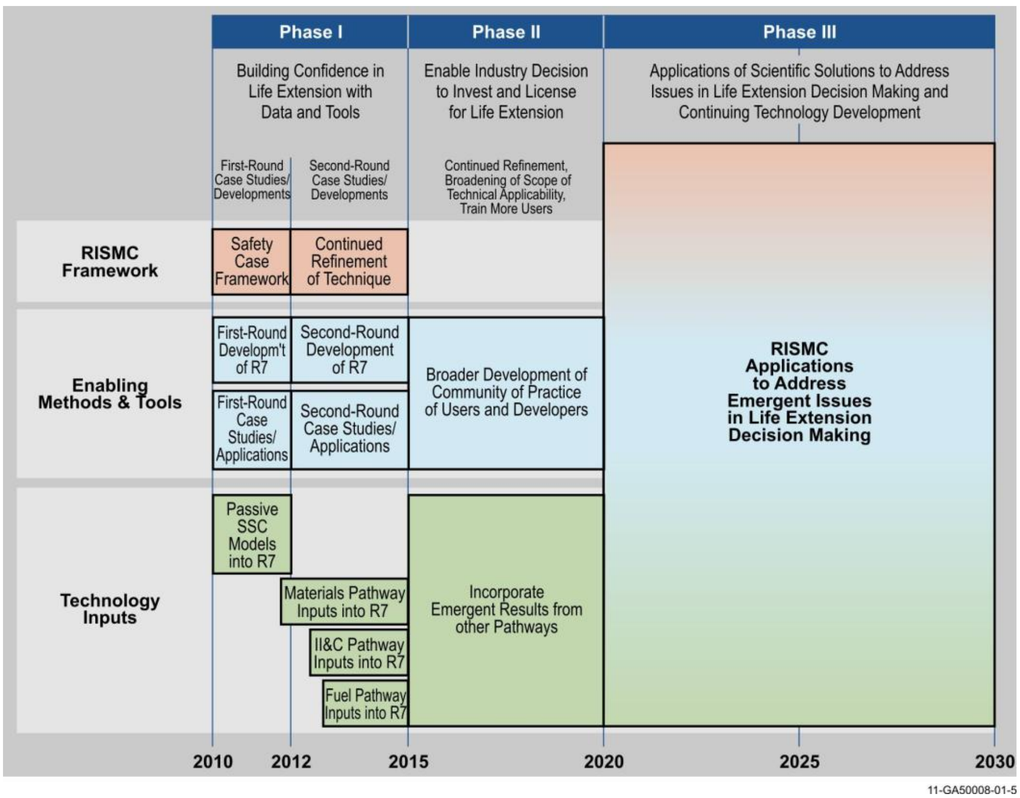


Figure 3-9. Risk-Informed Safety Margin Characterization pathway implementation schedule.

3.5 Economics and Efficiency Improvement

3.5.1 Background and Introduction

Improving the economics and efficiency of the current LWR fleet and maintaining excellent safety performance is a primary objective of the LWRS Program. Power uprates have been the most important methods that enable enhancement of the economic performance of the current operating fleet of LWRs. Cooling capability influences thermal efficiency and reliable operation. Increased reactor power and climate change concerns place more burdens on cooling requirements. Expanding the current fleet into nonelectric applications would further increase the value of LWR asset owners. This R&D pathway will focus on three activities: (1) alternative cooling technologies, (2) nonelectric applications (process heat), and (3) power uprates.

3.5.1.1 Alternative Cooling. Water consumed by thermoelectric power plants (such as those fueled by coal, natural gas, and nuclear) continues to receive increasing scrutiny as new power plants are proposed and existing power plants encounter water shortages. Climate change may exacerbate the situation through hotter weather and disrupted precipitation patterns that promote regional droughts. Before 1970, thermoelectric power plants addressed their need for cooling with either fresh or saline water withdrawals for once-through cooling. Since that time, closed-cycle systems (evaporative cooling towers or ponds) have become the dominant choice, with certain impacts on water usage. Figure 3-10 shows the Limerick nuclear power plant in Pennsylvania, which uses mine pool water for a substantial fraction of its cooling.

Figure 3-10. Limerick nuclear power plant.

3.5.1.2 *Nonelectric Application (Process Heat).* Nuclear power plants have very high capital investment and low operating costs. Therefore, to minimize the cost of electricity, these nuclear power plants are typically operated at full power to provide base load needs. With the potential extended power uprates for these nuclear power plants in the future and the eventual construction of new nuclear power plants in the United States, some of the nuclear power plants may need to be operated at reduced power levels when electricity demand is low at off-peak times, such as during the night. This is an operating strategy seen in France where power demand must affect reactor output because of the high percentage of nuclear power. Operating nuclear power plants at a reduced power level is not desirable for economic and safety reasons. On the other hand, only about one-fifth of the world's energy consumption is used for electricity generation. Most of the world's energy consumption is for heat and transportation. The existing LWR fleet in the United States has limited experience in nonelectric applications. However, the existing LWR fleet might have some potential to penetrate into the heat and transportation sectors, which are currently served by fossil fuels that are characterized by price volatility, finite supply, and, more importantly, environmental concerns. There are a wide variety of purely thermal applications of a reactor's output, which may be integrated with an electrical generating plant. These applications may be effective even at the conventional steam temperatures that exist in commercial nuclear power plants. These nonelectric applications of nuclear energy include providing heat and steam to industrial processes, seawater desalination, and district heating. The desalination of seawater using nuclear energy has been demonstrated, and nearly 200 reactor-years of operating experience have been accumulated worldwide. District heat involves the supply of heating and hot water through a distribution system, which is usually provided in a cogeneration mode in which waste heat from power production is used as the source of district heat. Several countries have district heating using heat from nuclear power plants.

3.5.1.3 Power Uprates. The nuclear industry has been making improvements in commercial nuclear power plants since the 1970s to increase their rated power output (power uprates). There are three types of power uprates defined by NRC: (1) measurement uncertainty recapture power uprates are less than 2% and are achieved by implementing enhanced techniques for calculating reactor power, (2) stretch power uprates are typically up to 7% and are within the design capacity of the plant, and (3) extended power uprates, which are greater than stretch power uprates and have been approved for increases as high as 20%. The primary methods of producing more power are improvements in the fuel design, operational restriction, reanalyzed reactor thermal-hydraulic parameters, more involved safety analysis, and upgrade of the balance of plant capacity by component replacement or modification (such as replacing a high-pressure turbine). Instrumentation upgrades that include replacing parts, changing set points, and modifying software also are required for operation at increased power levels. As of today, NRC has approved 129 power uprate submittals. The total extra power generated from power uprates is equivalent to building almost six 1,000-MWe new nuclear power plants. Uprating a nuclear power plant reduces the operating cost per unit energy generated and significantly enhances the asset value of the plant owner.

The industry has achieved such remarkable performance by using available fuel designs, materials, and engineering methods. To facilitate additional power uprates, especially extended power uprates, new materials, methods, and fuel designs are needed. It is LWRS Program's role to conduct R&D leading to the new materials, methods, and fuel designs to enable additional extended power uprates.

The changes in the physical nuclear power plant systems are theoretically able to sustain much higher power uprates. An additional cycle of extended power uprates greater than 20% is being considered. To increase a nuclear power plant's power to levels greater than 20% requires higher power density core designs and scientific understanding of plant performance issues. Power uprate causes higher radiation fluences, increased thermal-induced stress and fluid-induced vibrations, and corrosion. The plant owners must have the confidence that the power uprate will not cause accelerated damage to the nuclear power plant structure, system, and components. For instance, the integrity of steam dryers and steam generators must be ensured due to increased steam loads and the integrity of reactor pressure vessels and core internals due to increased radiation damage and corrosion. The plants also must demonstrate with confidence that mandated safety limits will not be violated during accident conditions to ensure the fuel integrity due to increased duty and containment integrity because of higher storage energy of the reactor coolant system. The LWRS Program focuses on developing enabling technologies, such as revolutionary fuel design, that offers superior safety and economic performance and modern design and safety analysis tools that can resolve extended power uprate inhibiting issues to significantly advance the potential for additional power uprates greater than 20%. Development of deep science-based knowledge also will be complemented by the DOE Energy Innovation Modeling and Simulation Hub, which is run by the CASL. The integration of results from CASL, plant changes, and operating conditions will be evaluated by the Economics and Efficiency Improvement R&D pathway to facilitate implementation of extended power uprates. An advanced study of these effects in an existing and aging plant is required. The ability to greatly uprate a nuclear power plant provides the national strategic benefits of increasing the total nuclear power supply at a lower cost per kW than building new nuclear plants. The previous success of power uprates makes this an attractive way to expand nuclear power supplies.

3.5.2 Vision and Goals

The commercial nuclear power industry will undertake additional power uprates beyond 20%. These uprates will require optimized cooling technology to minimize water usage to accommodate the uprated power output. The increased power available also can facilitate expansion of nonelectric applications within the framework of plant life extension to optimize the contribution of nuclear power to the national strategic benefits of low emissions energy production.

The programmatic goals for this R&D pathway are captured in the following statements:

1. Alternative Cooling Technology: Conceive, develop, and establish deployable technologies for optimizing use in the nuclear energy thermocycle, while minimizing reliance on water resources at the same time.

2. Nonelectric Application (Process Heat): Develop the energy conversion and heat transport technologies needed for applications of existing LWRs to low temperature process heat.

3. Power Uprates: Provide scientific and engineering solutions to facilitate extended power uprates for all operating LWRs in a cost-effective manner.

3.5.3 Highlights of Research and Development

3.5.3.1 Alternative Cooling. Alternatives to closed-cycle cooling (e.g., wet cooling tower) are generally dry cooling (e.g., waste heat rejected to the atmosphere) or hybrid cooling (e.g., using aspects of both wet and dry cooling), as well as replacing freshwater supplies with degraded water sources. Degraded water is polluted water that does not meet water-quality standards for various uses such as drinking, fishing, or recreation. Existing operating LWRs in the United States use either once-through cooling or wet cooling towers, with a few using degraded water.

It is essential to provide adequate and timely cooling for safe and economic operation of nuclear power plants. With more stringent regulation on the temperature of the discharged cooling water from a nuclear power plant, the potentially decreased availability of clean cooling water, increased cooling load with the power uprates, and potentially warmer weather in the summer season due to global climate change, alternative and potentially advanced cooling technology has to be developed in order to ensure the reactors can be safely and economically operated without being forced to shut down or reduce the power output due to cooling water issues. R&D activities will focus on the following: (1) technology development (such as advanced condenser design, reducing water losses in the wet cooling tower system, or improving dry cooling and hybrid cooling technology); (2) evaluating applicability of alternative water-conserving cooling technologies (such as dry cooling and hybrid cooling) to improve LWR plant efficiency, relieve the cooling water requirement, and expand use of alternative sources of water; and (3) improving analysis methodology, performing analysis to identify optimal designs, and developing water resource assessment and management decision support tools.

3.5.3.2 Nonelectric Application (Process Heat). Nuclear power plants produce 1,500 to 4,500 MW of steam. Very few markets exist for such large quantities of steam. Usually, it is not economical to modify a nuclear power plant to produce a few megawatts of heat to meet a local industry or district-heating need; therefore, district heating will not be considered. Seawater desalination using multi-stage distillation and existing LWRs also is a very remote possibility. Desalination using reverse osmosis, where most of the energy input is electricity, may be a viable, off-peak use of LWRs for economical fresh water production. Using nuclear energy indirectly for transportation by creating fuel ethanol has the potential to open new markets for existing LWRs. Cellulosic biomass-to-fuel ethanol plants require very large quantities of low-temperature steam that could be provided by LWRs if these plants were located close to the reactors.

Heat from nuclear power plants also can be used to provide process heat to a Fischer-Tropsch chemical process (or similar processes) to produce synthetic fuel. Coal gasification has the advantage of reduction of air emissions from coal combustion, an increased thermal efficiency of combustion, and use of a large resource base. Nuclear energy, being an industrially proven and nonpolluting technology, is a valid candidate for this purpose.

Technical and economic viability of different applications will be studied. One key issue to be addressed is interface design and plant modifications.

3.5.3.3 Power Uprates. R&D activities will be focused on enabling safe and cost-effective plant modifications and modernizations required to gain margins by enhancing the plant power limiting equipment capability. Consistent with the main themes currently identified in this R&D pathway, activities are planned in the following main areas to significantly uprate the current LWR power levels: (1) collaboration with Nuclear Materials Aging and Degradation R&D pathway on higher fluence effect, (2) innovative fuel design, fuel performance, and loading management, (3) high fidelity core physics and fuel depletion capability, (4) reactor thermal hydraulics, (5) safety assessment under high power, (6) balance of plant, including steam generators for pressurized water reactors, (7) operation with higher core outlet temperature, (8) instrumentation and control systems and software reliability and (9) integrated detailed physics from the DOE Energy Innovation Modeling and Simulation Hub.

3.5.4 Facility Requirements

No additional facilities are foreseen for alternative cooling technologies. Power uprates will leverage the facilities used in other R&D pathways.

3.5.5 Products and Implementation Schedule

The main products of this R&D pathway are as follows:

- Advanced cooling technologies that would reduce cooling water requirements and improve the plant's thermal efficiency
- Tools, methods, and technologies (collaborating with other pathways) to enable additional extended power uprates; these include innovative fuel designs (such as annular fuel design) to enable higher power density, improved reactor safety analysis tools, increased heat removal capabilities for containment, and economic analysis to guide power uprate decision-making
- Feasibility studies of the technical and economic viability of expanding the existing fleet into nonelectric applications.

The implementation schedule (Figure 3-11) is structured to support the following high-level milestones:

- 2015:
  - Preserve the once-through cooling technologies (advanced water conservation technologies for wet cooling tower)
  - Complete feasibility studies for process heat production and low-temperature distillation applications.
- 2020:
  - Ensure significant cost reduction of dry cooling technology and thermal efficiency improvement in the hot summer timeframe
  - Ensure next generation safety analysis tools available to support additional extended power uprates.
- 2025: Apply alternative and new cooling technologies.
- 2030: Enable 10-GWe extra capacity additions through additional extended power uprates.

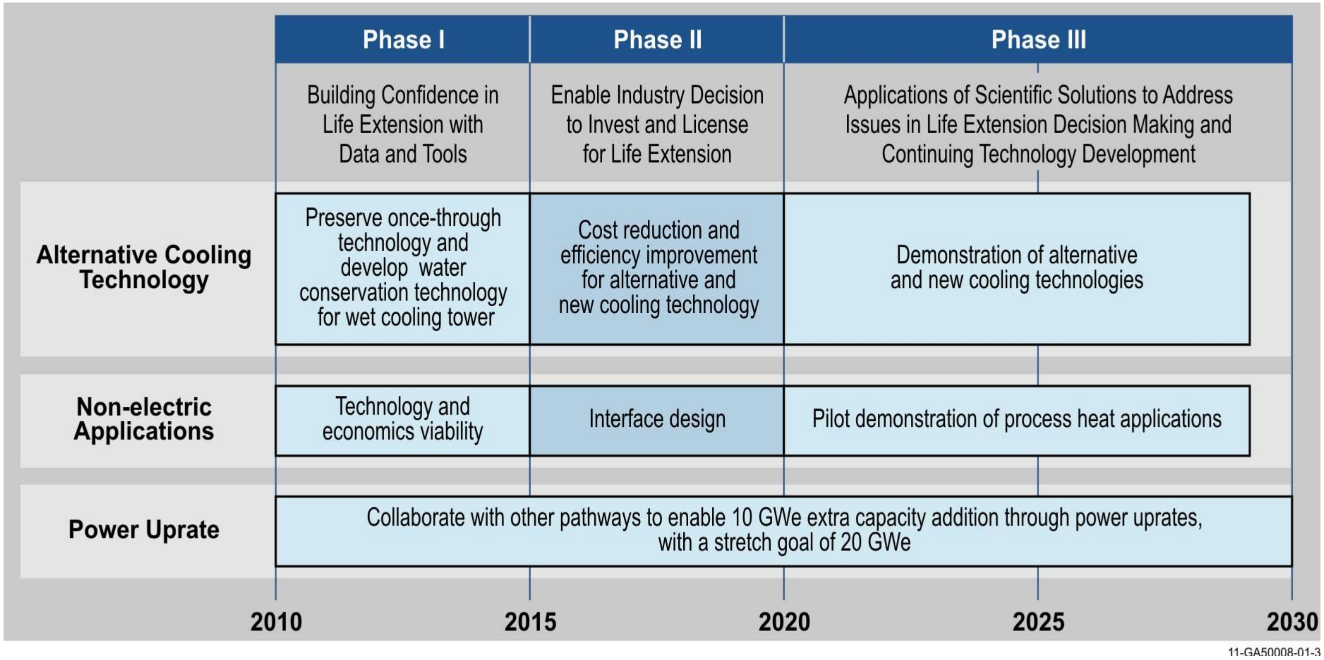


Figure 3-11. Economics and Efficiency Improvement pathway implementation schedule.

3.6 Pathway Crosscutting and Integration

The overall focus of the R&D activities will be on practically advancing the ability of the owner of nuclear assets to manage the effects of the aging of passive components and increase the efficiency and economics of operations. This will provide the necessary technology and ability to keep valuable nuclear power plant assets online and generating the required clean and safe energy. Transformational activities initially should be developed as limited-scope pilots that provide confidence in the program direction and developed technology. In selecting projects, it is vital that all consideration should be given to how each of the pathways can support achievement of safety and efficiency for existing LWRs by ensuring that each pathway is appropriately coordinated with the desired outcomes of the other pathways. Technical integration is an important and significant part of the LWRS Program. R&D within the program is integrated across scientific and technical disciplines in the five R&D pathways. The LWRS Program is integrated with outside sources of information and parallel R&D programs in industry, universities, and other laboratories, both domestic and international. Different methods of integration are used depending on the situation and goals.

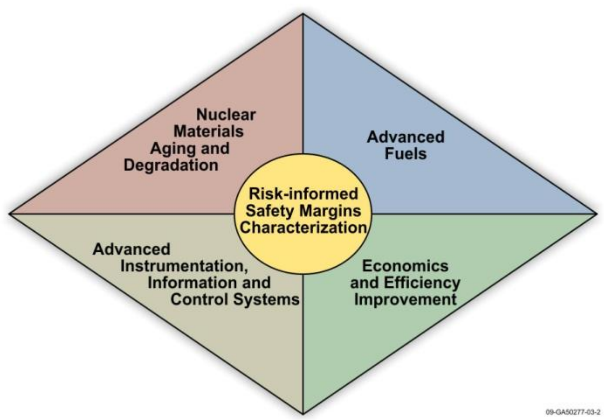


Figure 3-12. Integration of five research and development pathways.

3.6.1 Technical Integration

Interfaces between R&D pathways and the required integration across them are naturally defined by common objectives for materials and fuel performance and the system monitoring of their performance. Similarly, interface and integration of the pathways with the RISMC R&D pathway is defined by data and models, which affect performance, monitoring, and control (Figure 3-12).

Data and information from the Nuclear Materials Aging and Degradation, Advanced LWR Nuclear Fuel, and Economics and Efficiency Improvement R&D pathways will be fed into the RISMC models. Results of the RISMC analysis will guide development of advanced fuels; materials aging and degradation mitigation; advanced II&C systems; and economics and efficiency improvement. Examples of some crosscutting areas in the LWRS Program include coolant chemistry effects, crack growth mitigation effects, irradiation testing, irradiation source term changes, improved online monitoring of reactor chemistry, advanced instrumentation for the study of system degradation, fuel failure mechanisms, creation of SSC aging database, advanced measurement techniques, field testing and data collection/capture, nondestructive evaluation/assay tools, and advanced inspection techniques.

3.6.2 Advanced Modeling and Simulation Tools

The most common theme for the R&D pathways is use of computer modeling of physical processes or development of a larger system computer model. Extensive use of computer modeling by the R&D pathways is intended to distill the derived information so that it can be used for further research in other pathways and as the basis for decision-making. A cross-cutting implementation plan is being developed to address the interfaces for each of the pathways.

Computer modeling occurs in three forms with many overlapping aspects within the LWRS Program. Modeling a physical behavior (such as crack initiation in steel) is an example of direct computer modeling. The resulting model is used to store information for use in other pathways and to use in its own right for further research.

A second computer modeling activity is development of more detailed computer modeling tools capable of encoding more complex behaviors. One of the intended outcomes from Advanced LWR Nuclear Fuels Development research is new modeling tools that can describe behavior of such complexity that current computer models are incapable of producing. The increased accuracy will allow improved results to be incorporated into other pathways.

The final computer modeling improvement is creation of larger integrated databases that roll up results and allow decision-making. The large, system-wide, integrated models allow complex behavior to be understood in new ways and new conclusions to be drawn. These integrated databases can be used to further guide physical and modeling research, improving the entire program.

Because of their overlapping nature and numerous interfaces, these modeling activities tend to be naturally cross-cutting activities between R&D pathways. A separate cross-cutting implementation plan is being developed that will address the details of these interfaces and means of handling these overlaps for the LWRS Program and other DOE-NE programs.

3.6.2.1 Nuclear Energy Advanced Modeling and Simulation. A critical interaction of the LWRS Program is with the DOE Nuclear Energy Advanced Modeling and Simulation Program. The LWRS Program will take advantage of the detailed, multiscale, science-based modeling and simulation results developed by the DOE Nuclear Energy Advanced Modeling and Simulation Program that will be uniquely valuable to multiple R&D pathways. The modeling and simulation advances will be based on scientific methods, high dimensionality, and high resolution integrated systems. The simulations will use the most advanced computing programs available. These tools will be fully three-dimensional, high-resolution, modeling-integrated systems based on first-principle physics. To accomplish this, the modeling and simulation capabilities will have to be run on modern, highly parallel processing computer architectures. These advanced computational tools are needed to create a new set of modeling and simulation capabilities that will be used to better understand the safety performance of the aging reactor fleet. These capabilities will be information sources and tools for advancing the LWRS Program goals.

3.6.2.2 DOE Energy Innovation Modeling and Simulation Hub. The LWRS Program also will take advantage of the progress made by the DOE Energy Innovation Modeling and Simulation Hub managed by the Consortium for Advanced Simulation of Light Water Reactors (CASL). The Hub will support the LWRS Program by addressing long-term operational challenges faced by U.S. nuclear utilities. The alignment between the Hub and the LWRS Program's technical activities is by providing detailed calculations and large integrated models that address each of the technical needs of the LWRS Program R&D pathways.

A primary initial product of the Hub is a sophisticated integrated model of a LWR (a virtual reactor). The virtual reactor will be used to address issues for existing LWRs (e.g., life extensions and power uprates). The Hub challenge problems have been selected principally to demonstrate the capability of the virtual reactor to enable life extensions and power uprates. The enhanced computational capability of the virtual reactor will allow simulated proof of concepts for LWRS improvements and identify areas needing additional research.

With improvements in modeling and simulation capability centered on a science-based approach, the Hub will enable exploration of advanced fuel design features. These advanced features may range from modifications of the current compositions of the zirconium-based alloys now used for cladding to the development of entirely new cladding materials, new fuel materials with higher densities and improved thermal properties, and changes in fuel geometry and configuration. The virtual reactor capability will progress from analyses of operating reactors to design improvements. Improved modeling and simulation of the reactor internals and steam generators will support the needs of the Nuclear Materials Aging and Degradation and Economics and Efficiency Improvement R&D pathways. The virtual reactor performance will also provide modeling inputs for the Advanced Instrumentation, Information, and Control System Technologies R&D pathway.

3.6.3 Coordination with Other Research Efforts

In order to encourage communication and coordination with outside experts and parallel programs, the LWRS Program will be aware of issues and changes of technical needs that affect long-term, safe, and economical operation of existing operating LWRs, and share information and resources with other professionals and programs that can assist the LWRS Program to provide timelier, less expensive, and better solutions to the needs and issues.

Primarily, coordination will be with the EPRI Long-Term Operation Program. At the program level, formal interface documents will be used to coordinate planning and management of the work. This will provide a ready source of information from EPRI's Nuclear Power Council and through their contact with utilities. At the R&D project level, both programs encourage frequent communication and collaboration.

Consistent with the vision of the LWRS Program, working relationships have been established with international organizations in FY 2009 and will continue in FY 2010 and beyond. The goal is to facilitate communication and cooperative R&D with international R&D organizations.

R&D needs for existing LWRs are synergistic with those for the GEN III+ LWRs to be deployed and LWR small modular reactors being designed and licensed. Consequently, scientific solutions developed from Objective 1 are directly applicable to the technological challenges facing deployment and operation of GEN III+ LWRs and LWR small modular reactors as described in Objective 2.

3.6.4 Performance of Technical Integration and Coordination

The LWRS Program will lead and encourage technical integration and coordination of issues affecting the LWR Long-Term Operation Program using methods that best match the issue. For known gaps in data, understanding, or technology, the LWRS Program will plan and manage integrated R&D projects through the LWRS Program TIO and its multiple interfaces.

To accommodate currently unknown issues or gaps in technology that may arise as result of ongoing R&D or nuclear power plant operations, a broader approach is necessary. This approach should include active internal and external communication with professional organizations, industry groups, and interdisciplinary teams for project and program reviews. The steering committee is an essential part of this process. The LWRS Program encourages participation in professional technical societies and national standards committees.

4. PROGRAM MANAGEMENT

4.1 Organization Structure

The entire LWRS Program falls within DOE-NE. Program management and oversight, including programmatic direction, project execution controls, budgetary controls, and TIO performance oversight, are provided by the DOE Office of LWR Technologies in conjunction with the DOE Idaho Operations Office. The functional organization, reporting relationships, and roles and responsibilities for the TIO are explained in the following sections and are shown in Figure 4-1.

The DOE Office of LWR Deployment directs the program, establishes policy, and approves scope, budget, and schedule for the program through the LWRS Program Federal Program Director. The DOE LWRS Program Federal Program Director is assisted with program management and oversight by DOE Idaho Operations Office.

DOE Idaho Operations Office will provide technical and administrative support to the LWRS Program. This support includes activities such as assisting in development of administrative requirements in support of contracting actions, conducting merit reviews and evaluations of applications received in response to program solicitations, performing all contracting administration functions, and providing technical project management and monitoring of assigned projects.

The TIO basic organizational structure is used to accommodate the crosscutting nature of the proposed R&D pathways. This organization is responsible for developing and implementing integrated research projects consistent within the LWRS Program’s vision and objectives. Additionally, the TIO is responsible for developing suitable industry and international collaborations appropriate to individual research projects and acknowledging industry stakeholder inputs to the program.

Within the TIO structure is the TIO director, deputy director, operations manager, each of the five R&D pathway leads, and an external steering committee. Nuclear industry interfaces and stakeholders’ contributions are accommodated in program development and project implementation actions through the TIO management structure. Recognition of continuing industry collaborations, reflecting issues and concerns necessary to extend plant licenses, are incorporated through the same program development and implementation actions.

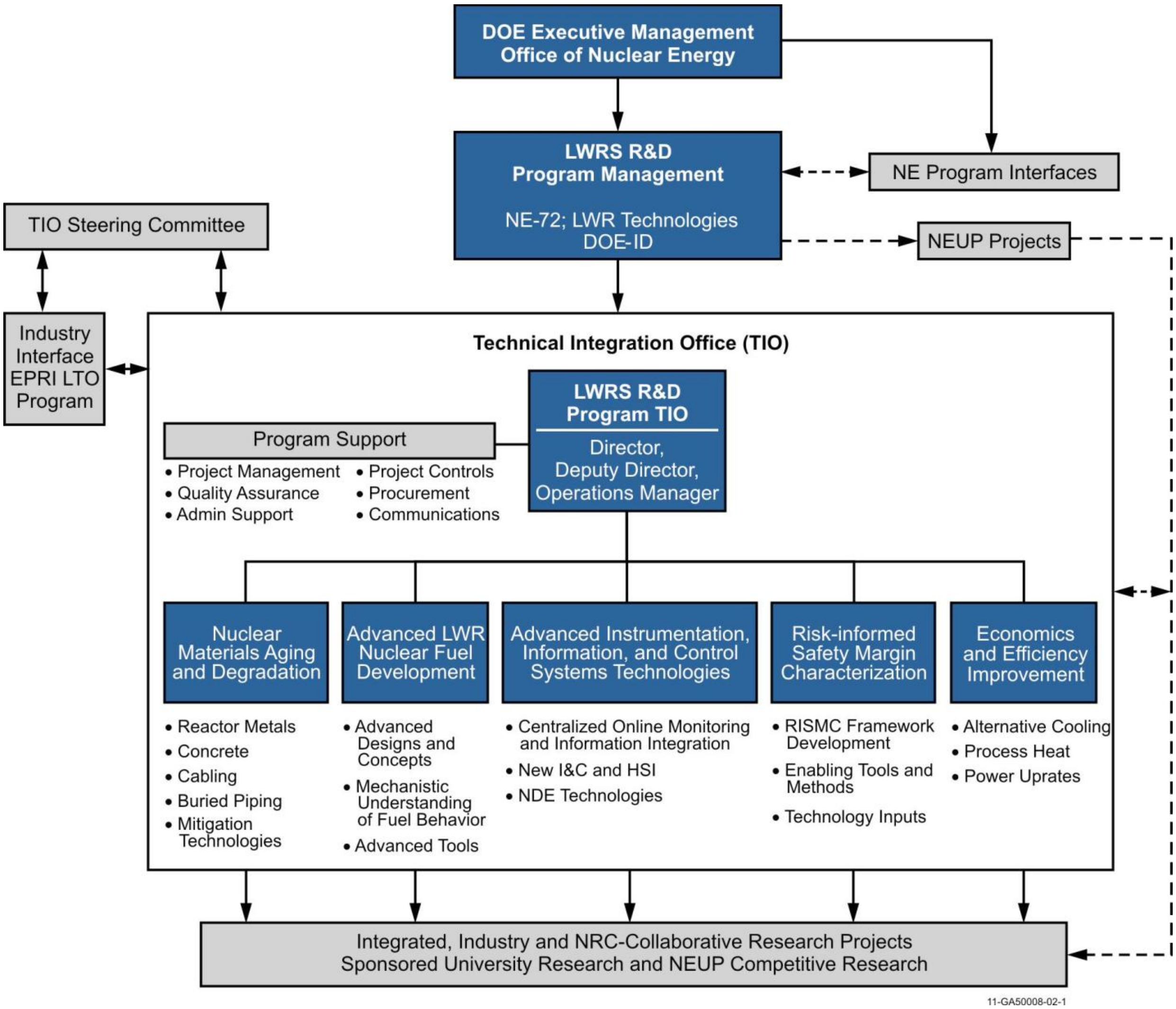


Figure 4-1. Light Water Reactor Sustainability Program organization.

4.2 Roles, Responsibilities, Accountabilities, and Authorities

4.2.1 Department of Energy Office of Nuclear Energy

DOE is responsible for the federal government’s investments in nuclear power R&D and incentive programs, which all further the Nation’s supply of clean, dependable nuclear-generated electricity. The LWRS Program conducts research that enables licensing and continued reliable, safe, long-term operation of current nuclear power plants beyond their initial license renewal period. The DOE Office of LWR Technologies directs the program, establishes policy, and approves scope, budget, and schedule for the program through the LWRS Program Federal Program Director. The LWRS Program Federal Program Director is assisted with program management and oversight by DOE Idaho Operations Office.

The essential programmatic DOE functions include, but are not limited to, the following:

- Establish program policy and issue program guidance

- Establish requirements, standards, and procedures
- In cooperation with TIO, establish requirements and develop strategic and project plans
- Establish performance measures and evaluate progress
- Represent the DOE program to other government agencies.

4.2.2 Technical Integration Office

TIO supports the LWRS Program Federal Program Director. The program is a cost-shared, collaborative program aimed to meet the needs of a diverse set of stakeholders. In addition to supporting national policy (energy and environmental security needs), the program supports agreed upon technical needs of NRC in assessing safety and relicensing requests for nuclear power plant extended life operation. It also supports industry needs for data and planning tools for long-term safe economical operation of their nuclear power plants. TIO is staffed with a director (including a deputy director and operations manager), R&D pathway leads, and program management staff. The director and leads are well-known technical and management experts from DOE laboratories. The TIO is structured and staffed to provide the program director with strong interfaces and communications with stakeholders, R&D plans based on stakeholder needs, proposals for R&D-specific projects and budgets, management of the projects (including funding), and communication of the results.

The LWRS Program TIO utilizes personnel from across the DOE laboratory complex. The intent of the organization is to staff the program with the right people to accomplish the work, regardless of location or affiliation. As appropriate, the technology integration and execution activities will use facilities and staff from multiple national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries.

TIO functions include the following: maintaining the long-range technical strategy plan for the LWRS Program, maintaining the LWRS Program Plan, developing annual project scope statements, monitoring authorized project work, coordinating weekly/monthly status meetings, coordinating periodic technical review meetings, providing formal status reporting, maintaining baseline change control, and performing project closeout planning and completion.

4.2.2.1 Technical Integration Office Leadership Team. The TIO director provides general program execution and support for the LWRS Program. This position leads the planning, performance, and communication of results from the R&D pathways. The TIO director works with the deputy director, operations manager, program support team, and R&D pathway leads to integrate and ensure all requirements are well defined, understood, and documented through long-range planning. The TIO director works with the deputy director, operations manager and program support team to ensure proper annual financial planning, scoping, oversight, and scheduling of the project work. The TIO director and the steering committee oversee assignment of appropriate resources and evaluate and resolve R&D needs of the LWRS Program. The TIO director reports to the LWRS Program Federal Program Director.

4.2.2.2 Research and Development Pathway Leads. The TIO includes five R&D pathway leads for the major R&D areas currently developed. The leads are the technical managers for their pathways and are responsible for ensuring that technical planning, project management, and leadership is provided for each pathway. R&D pathway leads are the primary interface between technically diverse organizations that form the structure of the LWRS Program. They are responsible for integration and translation of project requirements into an overall implementation plan tailored to accomplish their assigned R&D mission. They are responsible for establishing scope, cost, and schedule of the R&D activities. They interface with other R&D pathway leads to ensure effectiveness of crosscutting activities.

4.2.2.3 Program Support Team. The program support staff is responsible for contractual operations of TIO and assists other parts of TIO to execute work. The team provides personnel with expertise in project management, quality assurance, procurement, project controls, and communications. They provide tools, structure, oversight, and rigor to maintain R&D schedules and interfaces with the LWRS Program. They also provide financial information to management (through the TIO director's office) and monitor technical progress and track milestones.

4.2.3 Project Monitoring and Evaluation

DOE and TIO use a variety of methods to provide oversight of their projects, including semiannual project reviews, periodic progress reports, and scheduled evaluations, invoice reviews, and participation in periodic project meetings and conference calls.

4.2.3.1 Project Reviews. DOE and TIO conduct semiannual and annual project progress review meetings with project participants, including all R&D pathway leaders. During these project review meetings, project activities, schedule progress, and cost are discussed in detail. Status of deliverables, funding, or schedule concerns and potential changes in scope also are discussed. Performance expectations for the remainder of the budget period and project are reviewed. On an annual basis, DOE staff reviews the work scope, budget requirements, schedule, deliverables, and milestones for the subsequent budget periods. This often requires face-to-face meetings with project participants to fully understand the future planned work.

4.2.3.2 Periodic Project Status Meetings and Conference Calls. DOE, TIO, and R&D pathway leaders participate in periodic project status meetings and conference calls. Typically, project conference calls are the method of choice because of the number and location of participants; they are held at least twice a month. In addition, DOE staff participates in TIO conference calls on specific tasks.

4.2.3.3 Monthly Progress Reporting. DOE personnel review and evaluate project monthly progress reports for the project task and activity progress, accomplishment of deliverables, and budget and cost status. This reporting provides project participants and DOE staff with a monthly snapshot of overall project cost and schedule performance against the project baseline.

4.3 Interfaces

The LWRS Program TIO is intended as a national organization and is expected to have multiple national laboratory, governmental, industrial, international, and university partnerships. As appropriate, the LWRS Program technology development and execution activities will use facilities and staff from national laboratories, universities, industrial alliance partners, consulting organizations, and research groups from cooperating foreign countries.

TIO is responsible for ensuring the necessary memorandum purchase orders, interagency work orders, or contracts are in place to document work requirements, concurrence with work schedules and deliverables, and transfer funds to the performing organizations for R&D activities.

4.3.1 Steering Committee

A TIO steering committee advises TIO on the content, priorities, and conduct of the steering committee. The committee is comprised of technical experts selected and agreed upon by the TIO director and the LWRS Program Federal Program Director. The committee, as a group, is knowledgeable of the various R&D needs of DOE, industry, and NRC; ongoing and planned research as related to nuclear power technology; and policies and practices in public and private sectors that are important for the collaborative R&D program. The TIO director, in consultation with the steering committee, may form ad hoc subcommittees to review specific technical issues.

4.3.2 Industry

Planning, execution, and implementation of the LWRS Program are done in coordination with U.S. industry and NRC to assure relevance and good management of the work. The LWRS Program addresses some of the most pressing R&D needs identified in the Strategic Plan for Light Water Reactor Research and Development, including R&D needed by currently operating LWRs to extend their safe economical lifetime to significantly contribute to the long-term energy security and environmental goals of the United States.

The LWRS Program works with industry on nuclear energy supply technology R&D needs of common interest. The interactions with industry are broad and include cooperation, coordination, and direct cost-sharing activities. The guiding concepts for working with industry are leveraging limited resources through cost-shared R&D with industry, direct work on issues related to the long-term operation of nuclear power plants, the need to develop state-of-the-art technology to ensure safe and efficient operation and the need to focus government-sponsored R&D on the higher-risk and longer-term projects incorporating scientific and qualitative solutions. These concepts are included in memorandums of understanding, nondisclosure agreements, and cooperative R&D agreements.

Cost-shared activities are planned and executed on a partnership basis and should include significant joint management and funding.

EPRI has established the Long-Term Operations Program to run in parallel with the DOE LWRS Program. The Long-Term Operations Program is based on the LWR R&D Strategic Plan and focuses on long-term operations of the current fleet. EPRI and industry’s interests are applications of the scientific understanding and the tools to achieve safe, economical, long-term operation. Therefore, the government and private sector interests are similar and interdependent, leading to strong mutual support for technical collaboration and cost sharing. Formal interface agreements between EPRI and the TIO will be used to coordinate collaborations. Contracts with EPRI or other businesses may be used as appropriate for some work.

The LWRS Program has a steering committee with a diverse and experienced membership, including EPRI and utility members. The steering committee provides strategic guidance that helps ensure the program remains focused on useful industry results.

Each of the R&D pathways has interactions with the industry where detailed work packages are formed. DOE research is centered on general technology that advances and creates the knowledge base that will support individual applications for license renewals. The programmatic issue selection was created by the pathway definition that occurred with industry at the start of the LWRS Program. The technical pathway goals have been selected to drive the program toward solving problems that industry has been or will be unable to solve. The industry view does not look across the current commercial reactor fleet as generically or into the future as far as the DOE R&D. The ability of the LWRS Program to solve large, complex, and higher risk technical problems is a programmatic strength. The EPRI Long-Term Operation Program and LWRS Program cooperate to keep near-term research with EPRI and mid-term results aligned with LWRS objectives.

4.3.3 International

DOE is coordinating our LWRS Program activities with several international organizations with similar interests and R&D programs. We expect to continue to develop these contacts to provide timely awareness of emerging issues and their scientific solutions. A close working relationship with the Organization for Economic Cooperation and Development's Halden Reactor Project and with Electricite de France's Materials Aging Institute are particularly important to the LWRS Program. As funding is available, the LWRS Program intends to initiate formal R&D agreements with both institutions.

4.3.4 Universities

Universities will participate in the program in at least two ways: (1) through the Nuclear Energy University Program and (2) with direct contracts. In addition to contributing funds to the Nuclear Energy University Program, the LWRS Program will provide to the Nuclear Energy University Program descriptions of research from universities that would be helpful to the LWRS Program. In some cases, R&D contracts will be placed with key university researchers.

4.3.5 Nuclear Regulatory Commission

DOE's mission to develop the scientific basis to support both planned lifetime extension up to 60 years and lifetime extension beyond 60 years and to facilitate high-performance economic operations over the extended operating period for the existing LWR operating fleet in the United States is the central focus of the LWRS Program. Therefore, more and better coordination with industry and NRC is needed to ensure that there is a uniform approach, shared objectives, and efficient integration of collaborative work for LWRS. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that are executed among these groups. NRC has a memorandum of understanding[b] in place with DOE, which specifically allows for collaboration on research in these areas. Although the goals of NRC and DOE research programs differ in many aspects, fundamental data and technical information obtained through joint research activities are recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and to avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost sharing may be done in a mutually beneficial fashion.

[b] "Memorandum of Understanding Between U.S. Nuclear Regulatory Commission and U.S. Department of Energy on Cooperative Nuclear Safety Research," dated April 22, 2009, and signed by Brian W. Sheron, Director, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission and Rebecca Smith-Kevern, Acting Deputy Assistant Secretary for Nuclear Power Deployment, Office of Nuclear Energy, U.S. Department of Energy.